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Flight Service Evaluation of Kevlar-49 Epoxy Composite Panels in Wide-bodied Commercial Transport Aircraft

Tenth and Final Annual Flight Service Report

R.H. Stone

LOCKHEED-CALIFORNIA COMPANY
BURBANK, CALIFORNIA

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FOREWORD

This is the tenth and final annual flight service evaluation report on the condition of Kevlar-49 fairing panels installed on three L-1011s under NASA Contract NAS1-11621, "Flight Service Evaluation of Kevlar-49 Composite Panels in Wide-Bodied Commercial Transport Aircraft." The manufacture and installation of these panels was completed in February 1973 and reported in NASA CR-112250 dated March 1973 (reference 1). The results of inspections after the first nine years of flight service were reported in references 2 through 10. The original 5-year flight service program was extended for an additional 5 years through 1983. Annual reports have been issued describing service performance after each year of service through the 10 year duration of the program.

This program is being administered by the Langley Research Center, National Aeronautics and Space Administration, with Mr. Benson Dexter of the Materials Division as the project Engineer. The program is being performed by the Lockheed-California Company with Robert H. Stone the Program Leader, assisted by personnel of the Product Support Branch.

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FLIGHT SERVICE EVALUATION OF KEVLAR-49
EPOXY COMPOSITE PANELS IN WIDE-BODIED
COMMERCIAL TRANSPORT AIRCRAFT

Tenth and Final Annual Flight Service Report

R.H. Stone

Lockheed-California Company
Burbank, California

INTRODUCTION AND BACKGROUND

The subject program on flight service evaluation of Kevlar-49 fairings consists of fabrication, installation, and flight service evaluation of six secondary structural panels on each of three L-1011s. The three participating airlines are Eastern, TWA, and Air Canada. Fabrication and installation of the panels was completed in February 1973, with initiation of flight service occurring in early 1973 on all three aircraft.

In all of the prototype fairings Kevlar-49 fabric, comparable in fabric weave and thickness per ply to the baseline fiberglass, was substituted for the fiberglass on a ply-for-ply basis. This required no other design changes or development of new tooling for layup and cure, but still provided a savings in component mass of 25-30 percent. These six parts are as follows:

- A left-hand and right-hand set of large 152 by 170-cm (60- by 67-in.) sandwich wing-body fairing panels. The exterior skin is 0.05 cm (0.02 in.) thick with one ply of 181 style Kevlar-49 fabric and two plies of 120 style Kevlar-49 fabric. The interior skin is 0.04 cm (0.015 in.) thick with three plies of 120 style Kevlar-49 fabric. The honeycomb core is Nomex with 0.3 cm (1/8 in.) cells, and 0.05 gm/cm³ (3.0 lb/cu ft) density. Overall panel thickness is 2.36 cm (0.93 in.), with a solid laminate edge 0.30 cm (0.12 in.) thick, built up of 181 style Kevlar-49 plies (figure 1).
- A left-hand and right-hand set of small 14- by 83-cm (5.5-by 32.5-in.) solid laminate underwing fillet panels. The laminate incorporates nine plies of 181 style Kevlar-49 fabric and is approximately 0.23 cm (0.09 in.) thick (figure 2).

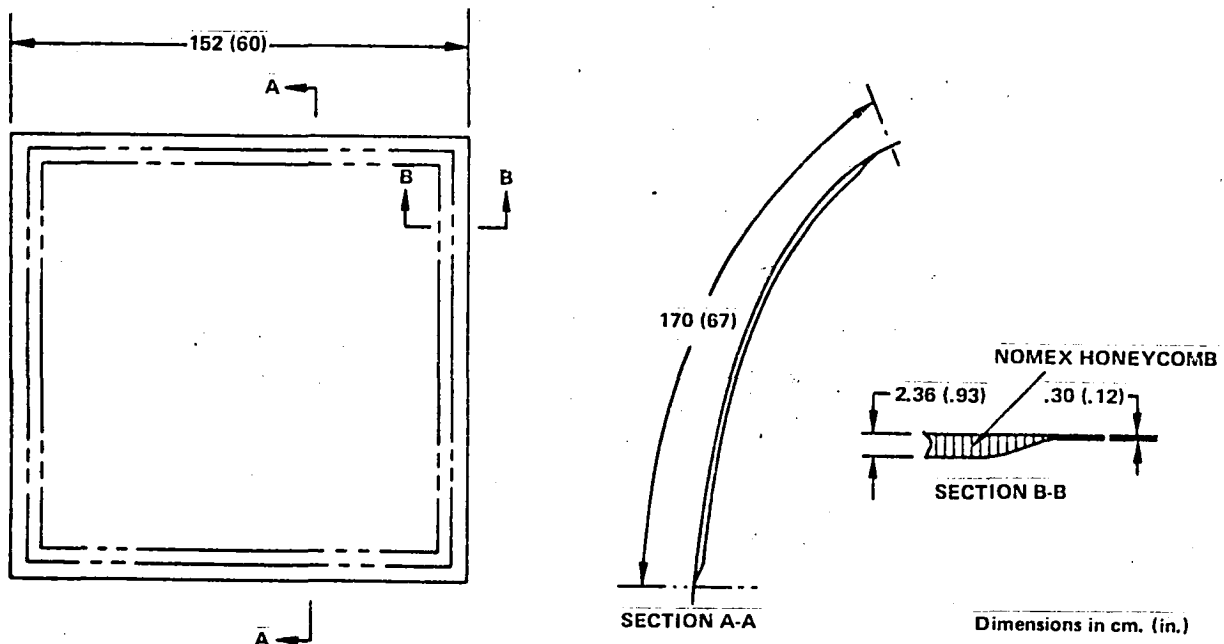


Figure 1. - Wing to body fairing panel.

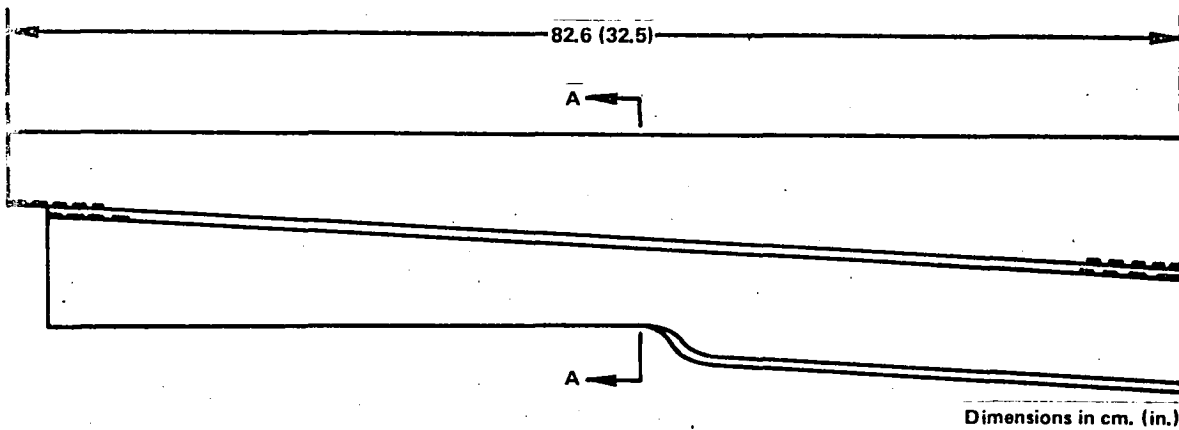
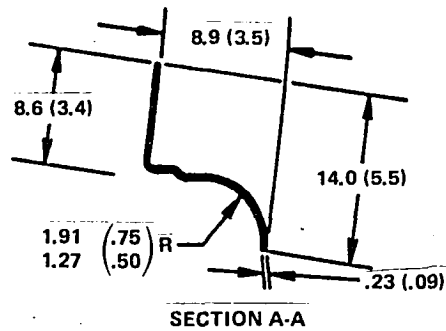


Figure 2. - Underwing fillet panel.

- A left-hand and right-hand set of aft engine sandwich fairings 76- by 208-cm (30- by 82-in.) approximately. The skins are 0.05 cm (0.02 in.) thick with one ply of 181 style Kevlar-49 fabric and two plies of 120 style Kevlar-49 fabric. The Nomex core is identical to that used in the wing-body fairing except for thickness, and the overall panel thickness is 0.64 cm (0.25 in.). The aft engine fairings has a solid laminate edge member 0.25 cm (0.10 in.) thick (figure 3).

The Kevlar-49 panels used the same resin system as the production fiber-glass parts. A 121°C (250°F) curing, 82°C (180°F) service epoxy (Hexcel's F-155) was used in the wing-body fairing and underwing fillet panels; and a 177°C (350°F) curing, 149°C (300°F) service epoxy (Hexcel's F-161) was used in the aft engine fairings. Two fabric weave styles of Kevlar-49 were used. The Kevlar-49 style 181 is an 8-harness satin weave similar to the 181 fiber-glass weave, 0.23 mm (9 mils) per cured ply and 0.17 kg/m² (5.0 oz/yd²) dry mass. Kevlar-49 style 120 is a plain weave, 0.13 mm (5 mils) per cured ply and 0.6 kg/m² (1.8 oz/yd²) dry mass. Both fabric styles incorporate light denier Kevlar-49 yarns, 380 denier for style 181, and 195 denier for style 120. The heavy denier yarns used in styles 281 and 285 Kevlar-49 fabric that are

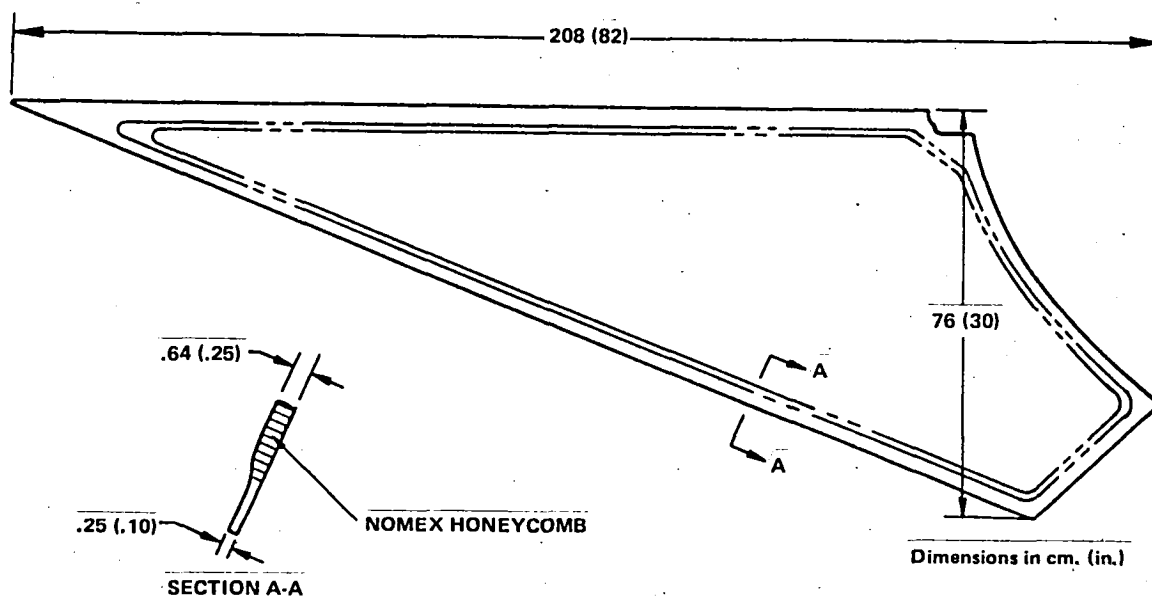


Figure 3. - Center engine fairing panel.

commonly used by the aircraft industry had not been developed at the time these parts were made.

All of the parts have an outer layer of flame-sprayed aluminum and top-coat applied according to standard production procedures used on the baseline fiberglass parts, and the sandwich parts have a film of clear bondable Tedlar on the inner skin as a vapor barrier. The actual savings in component mass achieved by this direct substitution of Kevlar-49 for fiberglass averaged 26 percent for the six parts. Further details on Kevlar-49 part design and fabrication are given in NASA CR-112250 (reference 1), which is the final report of the fabrication and installation phases of the program.

The first annual inspection results are given in NASA CR-132647 (reference 2). The Air Canada and TWA panels were inspected at Lockheed in this case due to special circumstances, while Eastern personnel inspected the Eastern panels at their Miami Maintenance Base.

For the second annual inspection and all subsequent inspections, the program scope was expanded as follows to obtain more complete information and documentation of part conditions:

- A Lockheed Engineering representative is present for each annual inspection at the airlines' maintenance bases.
- Three of the six panels (one of each left-hand and right-hand set) are removed for thorough inspection, weighing, and inspection of fastener holes and interior surface conditions.
- The airlines provide reports to Lockheed on all incidences of damage and repair occurring in service.

The second through the ninth annual inspections were conducted in accordance with this expanded scope, and are reported in references 3-10, respectively.

As discussed in previous reports, the TWA panels were removed after approximately 1 year (2400 hours) of service, and reinstalled on a second TWA L-1011 for continuation of flight service testing. The reinstallation on TWA aircraft N31030 required some rework and repair of the panels, particularly in the case of the aft engine fairing panels, where relocation of all

fastener holes was required. This rework activity is reported in detail in the Second Flight Service Report (reference 3). The aircraft on which these parts were installed was delivered to TWA in August 1975, and have since been inspected annually in accordance with the expanded program scope.

During 1977, a 5-year extension to the program was received from NASA for a total of 10 years of flight service of the Kevlar-49 fairings. This extension carried the program through 1983, and annual inspections of the three shipsets have taken place in accordance with the expanded program scope outlined above.

In 1978, Eastern disclosed plans to lease the aircraft with the Kevlar fairings to a foreign carrier, but stated a willingness to reinstall the fairings onto a second Eastern aircraft. Removal of the panels took place in 1979 and was discussed in the Sixth Flight Service Report (reference 7). The panels were reinstalled onto Eastern Ship N313EA during 1980, and this activity was discussed in the Seventh Flight Service Report (reference 8).

The fairings being evaluated in this program are the earliest Kevlar-49 components placed in commercial airline flight service, predating production applications of Kevlar-49 on commercial transports by several years. These components are exposed to over 2000 flight hours per year of typical aircraft operating environments; and detailed monitoring of the fairings' performance in this program provides information on long-term durability, damage tolerance, chemical resistance, and mechanical properties. Kevlar-49 fibers are the only organic reinforcing fibers used in aircraft structures, and have certain characteristics, such as moisture pickup in the fiber and low resin/fiber bond, which were of concern initially. The resistance of Kevlar-49 composites to long-term service environment as verified by the 10 years of flight service in this program provides confidence in the use of Kevlar-49 for additional aircraft structural applications.

PANEL INSPECTIONS

The tenth annual inspection of the Eastern fairings on Ship N313EA (Serial 1020) took place at Eastern's Atlanta Maintenance Base on July 5, 1983. This was the third inspection after reinstallation of the fairings onto

Ship N313EA in October 1980. The left-hand wing-body fairing and aft engine fairing panels were removed for inspection while the opposite set of panels were inspected on the aircraft. This was the opposite set to those removed in the 1982 inspection. The two underwing fillet panels were misplaced by Eastern after removal from the original aircraft in 1979 and have not been found.

The fairings had accumulated 1788 flight hours on Ship N313EA in the 9 months since their previous inspection for a utilization rate of 6.6 hours per day. This was a total of 7324 flight hours since their installation onto Ship N313EA in October 1980. The fairings had previously accumulated 17,718 flight hours on Ship N314EA for a total of 25,042 flight hours for the 10-year flight service program.

The inspection of the TWA fairings on Ship N31030 (Serial No. 1111) took place at TWA's Los Angeles Maintenance Base on October 14, 1983. The left-hand wing-body fairing panel, the right-hand underwing fillet panel, and the right-hand aft engine fairing panel were removed for inspection, while the opposite set of panels were inspected on the aircraft. These were the opposite parts to the wing-body and aft engine fairings removed in the previous inspection. The TWA right-hand underwing fillet has been removed at each annual inspection to obtain accurate mass determinations and detect any indication of continuing moisture pickup. Difficulty had been encountered in obtaining accurate mass determinations of the parts because of the lack of accurate balances at the airline maintenance bases. The proximity of TWA's base to the Lockheed plant made it feasible to bring in an accurate balance for the inspections. The sandwich panels are too large to weigh on this balance, but the underwing fillet can be readily weighed. This activity was initiated in 1978 on the right-hand part.

The TWA fairings had 25,440 flight hours on Ship 1111 as of the date of inspection. These fairings had been initially installed on Ship 1026, and accumulated 2404 flight hours on that ship prior to removal and reinstallation for a total of 27,844 flight hours for the 10-year flight service program. The parts had accumulated 3556 hours in the 13 months since the previous inspection for an average utilization of 9.0 hours per day.

The inspection of the Air Canada fairings on Ship CF-TNB-502 (Serial No. 1021) took place at Air Canada's Montreal Maintenance Base on February 17, 1984. The left-hand wing-body fairing, left-hand underwing fillet and right-hand aft engine fairings were removed for inspection while the opposite set of panels were inspected on the aircraft.

The fairings had accumulated 3428 flight hours on Ship 1021 in the 17 1/2 months since their previous inspection, for a utilization rate of 6.5 hours per day, and a total of 26,682 flight hours for the ten-year flight-service program.

Inspection of these panels was by visual examination and coin tapping for delaminations and skin-core disbonds. The panels taken off the aircraft were cleaned to remove excessive dirt and residue. The panels were then inspected for the condition of the fastener holes and the inner surface, as well as the outer surface condition which was checked on all six parts.

The inspections were conducted with the participation of Lockheed Engineering, and with the assistance of airline maintenance personnel in removal and reinstallation of the panels. Photographs were taken of all panels and areas containing defects, damage, or other conditions of special interest. Photographs were provided by a commercial photographer in Atlanta, by the Lockheed Photography Department at TWA in Los Angeles, and by Air Canada in Montreal.

Detail observations of the inspections are given in Appendices A, B, and C for Eastern, TWA and Air Canada, respectively.

The inspections reported herein complete all flight service program activities. Title for these fairings has been transferred to the participating airlines who have indicated they will keep the parts in service. A summary of the complete flight service program is given in Table 1.

DISCUSSION OF INSPECTION RESULTS

The Kevlar-49 panels have performed satisfactorily in service for ten years with no major damage or defects requiring corrective maintenance.

TABLE 1 - TEN-YEAR FLIGHT SERVICE EVALUATION PROGRAM SUMMARY

Airline	Tail No.	Serial No.	Flight Service Period	Total Flight Hours \triangle	Approx. Utilization Rate (Hrs/Day)
Eastern	N314EA	1022	Jan. 1973- Sept. 1979	25042	7.3
	N313EA	1020	Oct. 1980- July 1983		
TWA	N31007	1026	Apr. 1973- Apr. 1974	27844	8.3
	N31030	1111	Aug. 1975- Oct. 1983		
Air Canada	CF-TNB-502	1021	Jan. 1973- Feb. 1984	26682	6.6
TOTAL				79568	
\triangle Cumulative fairing flight-hours on both aircraft					

Minor impact damage has occurred, with complete penetration of the skins in some instances. Minor disbands have also been noted, along with some incidences of fastener hole elongation. A general condition of fraying around fastener holes, resulting from the initial machining operation, has been observed since the beginning of the program. The airlines do not regard these as serious occurrences as the fairings are lightly loaded nonstructural components which only take aerodynamic loads. Damage is therefore left unrepaired for an indefinite period or else given a cosmetic repair.

The incidences of new damage and damage growth noted in the 1983 inspections were:

1. Two small disbonds on the outer surface of the Eastern left-hand wing-body fairing.
2. A small crack and a small disbond on the inner surface of the TWA left-hand wing-body fairing.
3. Three small disbonds on the outer surface of the Air Canada left-hand wing-body fairing.
4. A disbonded and depressed area on the outer surface of the Air Canada right-hand wing-body fairing had increased significantly in size. Slight growth had also occurred in a disbond area on the outer surface of the Eastern right-hand wing-body fairing, and on two inner surface disbonds and one inner surface crack of the Air Canada left-hand wing-body fairing.

These disbonds and cracks, as well as similar conditions noted in previous inspections, are primarily the result of impact damage. The disbonds noted in this and previous inspections may have been caused by low-level impacts which did not produce a visible external crack. These cracks and disbonds have nearly all occurred on the wing-body fairings which are in an area more subject to ground-handling damage than the other parts. This is evidence that the disbonds are the result of low-level impact, but other possible explanations are manufacturing defects and localized excessive heat application. These disbonds may be interply delaminations rather than skin-core disbonds or may be a combination of both; but this distinction cannot be made with coin tapping and visual inspection.

The incidence of damage on these prototype parts is probably greater than for standard production parts because of the increased handling during removal and reinstallation for the annual inspections. The inner skin damage on the wing-body fairings may have occurred during removal and reinstallation, but there is an access bay above these parts containing hydraulic lines, and the inner skin damage may have occurred during maintenance activity in this area.

Damage growth was noted in only four instances in the 1983 inspections, and the damage remained minor in nature. This lack of damage growth is a significant indication of acceptable damage tolerance for Kevlar-49 in these

applications. In some cases cracks and disbonds have remained unchanged in appearance or size for eight years.

While some of the minor damage observed to date has not been repaired, several repairs have been made to the Kevlar-49 parts, mostly on the exterior surfaces of the wing-body fairing sandwich panels. In previous inspections, repairs have been noted in which cracks were filled with a resin filler and in one case coated with conductive paint. Other patches consist of overlays of adhesive tape; in one case the patch has been identified as aluminum speed tape with an overcoat of paint. At least one repair of each type has been noted on the inner surface of the wing-body fairing panels. No new repairs were noted in the 1983 inspections.

In summary, the repair procedures used on the fairings have been cosmetic field repairs typical of the procedures used for noncritical fiberglass parts, and adaptable to either line station or maintenance base operations.

The other damage condition which has been typically observed on the Kevlar-49 panels has been fraying and elongation of fastener holes. These have been minor conditions in all instances, which have not required maintenance action or repair. Elongation of the fastener holes has occurred in a random distribution, and has been noted on the underwing fillet panels to a proportionally greater extent than the other parts. The condition is comparable to hole elongation on similar fiberglass panels which is a fairly common occurrence according to airline reports. The cause of elongation is concentrated or nonuniform bearing loads possibly resulting from installation problems or excessive hole clearances. There has been relatively little increase in the incidence or severity of this elongation, and in the 1983 inspections there was no significant increase in elongation over the previous inspections.

The fastener hole fraying appears to be a general occurrence on Kevlar-49 holes and edges where less than optimum machining procedures have been used. The fraying noted on these parts appears to be primarily the result of the initial machining operation, as this condition has remained essentially unchanged with increasing service life. These parts were fabricated in 1972

when development of Kevlar-49 machining techniques was in a very early stage, and the degree of fraying may therefore be more severe than for currently fabricated parts. In previous inspections, it was observed that some of the aft engine fairings and underwing fillets had noticeably less fraying than others. This indicates that variations in machining techniques and operator skills at the time of installation was a significant factor in the degree of fraying. It was also noted that the elongated holes in the underwing fillets generally had more fraying than the other holes, indicating that in-service loads can aggravate the initial fraying. There is no evidence that the frayed condition in any way affects parts performance.

The fastener holes on the Eastern fairings were relocated at the time of their reinstallation onto Ship 1020 in October 1980. The original fastener holes were filled with chopped glass filled epoxy, and new holes were drilled. These new fastener holes have a great amount of fuzz which created the frayed appearance noted in other inspections, and this condition is much more pronounced than in any of the other Kevlar-49 parts, including the original fastener holes on the Eastern panels. This indicates that nonoptimum procedures and tools were used in drilling the relocated holes. Some holes were drilled partially through the chopped glass filled epoxy filler. These areas had no fuzz, but did have a greater incidence of elongation than has been noted for holes drilled through the Kevlar-49. No elongation was observed in any of the relocated holes drilled through the Kevlar-49. The frayed condition does not appear therefore to significantly affect performance of these parts. The fuzz was observed to be almost entirely on the inner surface.

The Kevlar-49 parts have not been affected to any discernible degree by exposure to Skydrol or other aircraft fluids, but the presence of Skydrol has been observed on all three components. The Skydrol appears to have attacked a brush-on vapor barrier coating on some of the aft engine fairings. Paint adhesion to the Kevlar-49 surfaces appears to be comparable to fiberglass parts, as would be expected.

The Kevlar-49 parts have been weighed on some occasions when they have been removed. The effects of paint loss, repainting, resealing, and repair

have masked any mass change due to moisture pickup; and determination of mass changes has been hampered by the lack of suitable balances at the airline maintenance bases. A balance has been brought from Lockheed to the TWA base in Los Angeles for weighing of the small underwing fillet panel in the last four inspections. Accurate mass determinations have been obtained on the right-hand fillet (Appendix B). Results to date show no significant weight change over four years; and the part apparently had reached moisture equilibrium by the time the weighings started in 1978, as would be expected.

GROUND-BASED ENVIRONMENTAL EXPOSURE⁽¹⁾

Along with the flight service evaluation, a ground exposure program is being conducted to determine the effects of outdoor environment on several composite material systems including Kevlar 49/F-155 and Kevlar 49/F-161. The test results of specimens exposed at six worldwide locations were reported in reference 5 for one and three years of exposure and in reference 9 for five and seven years of exposure. This report includes all available data for specimens exposed for ten years.

Three specimen types, flexure, short beam interlaminar shear (SBS), and compression, were tested to establish the effects of outdoor environmental exposure. The flexure specimens were nominally 7.6 cm (3.0 in.) long, 2.5 cm (1.0 in.) wide, and 0.32 cm (0.125 in.) thick. The flexure specimens were tested according to ASTM STD. D790 in three-point bending with a nominal span-to-thickness ratio of 16. The environmentally exposed surface was tested as the compression surface in the flexure test. The SBS specimens were nominally 1.59 cm (0.625 in.) long, 0.64 cm (0.250 in.) wide, and 0.32 cm (0.125 in.) thick. The SBS specimens were tested according to ASTM STD. D2344 with a nominal span-to-thickness ratio of four. The environmentally exposed surface was also tested as the compression surface in the three-point bend test used for the SBS specimens. The compression specimens were nominally 11.4 cm (4.5 in.) long, 0.64 cm (0.25 in.) wide, and 0.13 cm (0.05 in.) thick. The compression specimens were tested in an IITRI fixture (modified ASTM STD. D3410) with an unsupported gage length of

(1) Work performed by H. Benson Dexter of the NASA Langley Research Center.

0.64 cm (0.250 in.). Fiberglass tabs, nominally 0.13 cm (0.05 in.) thick, were adhesively bonded to the specimen surface for load introduction.

Tables 2, 3, and 4 show the flexure, short beam interlaminar shear, and compression strengths, respectively, for specimens exposed for ten years at the locations indicated. The specimens from the Brazil exposure rack will not be tested until the summer of 1984. Figures 4 through 9 show average strength retention ratios for specimens tested after one, three, five, seven, and ten years of exposure at the six exposure locations indicated on the figures. The strength retention ratio is a comparison of the average specimen strength after exposure with the average baseline (no exposure) strength for the material system. The Kevlar/F-155 flexure specimens (figure 4) showed an average strength reduction of ten percent after one year of exposure and an average strength reduction of about 20 percent after ten years of exposure. The Germany exposure appears to be the least severe, whereas, the Hawaii exposure appears to be the most degrading on the flexure strength of Kevlar 49/F-155. The Kevlar/F-161 flexure specimens (figure 5) showed an average strength reduction of only about ten percent after ten years of exposure. The average flexural modulus (table 2) showed a reduction of about ten percent after ten years of exposure for both Kevlar material systems.

The results for the SBS specimens are somewhat more erratic than the flexure results. The average SBS strength reduction after ten years of exposure is about 22 percent (figure 6) for the Kevlar/F-155 material system. The Germany environment is the least degrading; however, no consistent pattern is evident for the most degrading environment. Although the ten year results are not available for the Brazil exposure, it appears that the Brazil environment may be the most degrading based on the one, three, and seven year test results. The average SBS strength reduction after ten years of exposure is about ten percent (figure 7) for the Kevlar/F-161 material system. For some unknown reason, extreme data scatter is evident after five years of exposure. The SBS strengths range from a 13 percent increase for the Hawaii and Germany exposure to a 19 percent decrease for the California exposure.

TABLE 2 - RESULTS OF GROUND-BASED ENVIRONMENTAL EXPOSURE ON
KEVLAR/EPOXY FLEXURE PROPERTIES

Exposure time, yr	Exposure location	Kevlar/epoxy system	Number of specimens	Average failure stress		Average flexure modulus	
				MPa	ksi	GPa	msi
0 (Baseline)	LaRC	F-155	6	396.2	57.46	25.0	3.63
10	LaRC	↓	3	321.2	46.59	19.5	2.83
10	California		3	310.2	44.99	20.0	2.90
10	New Zealand		3	319.4	46.32	19.5	2.83
10	Hawaii		3	296.6	43.02	18.8	2.72
10	Germany		3	346.3	50.22	22.1	3.20
10	Brazil		(Unavail.)	-----	-----	-----	-----
0 (Baseline)	LaRC	F-161	5	375.4	54.45	24.4	3.54
10	LaRC	↓	3	341.8	49.58	20.6	2.99
10	California		3	327.9	47.56	22.8	3.30
10	New Zealand		3	346.3	50.22	21.7	3.15
10	Hawaii		3	342.5	49.68	22.1	3.20
10	Germany		3	353.9	51.33	24.1	3.49
10	Brazil		(Unavail.)	-----	-----	-----	-----

TABLE 3 - RESULTS OF GROUND-BASED ENVIRONMENTAL EXPOSURE ON
KEVLAR/EPOXY SHORT BEAM INTERLAMINAR SHEAR STRENGTH

Exposure time, yr	Exposure location	Kevlar/epoxy system	Number of specimens	Average failure stress	
				MPa	ksi
0 (Baseline)	LaRC	F-155	7	47.8	6.94
10	LaRC	↓	3	37.2	5.40
10	California		3	37.3	5.41
10	New Zealand		3	35.9	5.20
10	Hawaii		3	35.6	5.16
10	Germany		3	39.7	5.76
10	Brazil		(Unavail.)	----	----
0 (Baseline)	LaRC	F-161	5	32.4	4.70
10	LaRC	↓	2	28.6	4.15
10	California		3	29.4	4.26
10	New Zealand		3	29.8	4.32
10	Hawaii		3	28.6	4.15
10	Germany		2	29.5	4.28
10	Brazil		(Unavail.)	----	----

TABLE 4 - RESULTS OF GROUND-BASED ENVIRONMENTAL EXPOSURE ON
KEVLAR/EPOXY COMPRESSION STRENGTH

Exposure time, yr	Exposure location	Kevlar/epoxy system	Number of specimens	Average failure stress	
				MPa	ksi
0 (Baseline)	LaRC	F-155	5	137.3	19.92
10	LaRC	↓	3	112.5	16.31
10	California		3	116.4	16.88
10	New Zealand		3	106.9	15.51
10	Hawaii		3	100.9	14.63
10	Germany		3	121.3	17.60
10	Brazil		(Unavail.)	-----	-----
0 (Baseline)	LaRC	F-161	5	128.0	18.56
10	LaRC	↓	3	103.5	15.01
10	California		3	114.2	16.57
10	New Zealand		3	104.7	15.18
10	Hawaii		2	98.2	14.24
10	Germany		3	118.0	17.11
10	Brazil		(Unavail.)	-----	-----

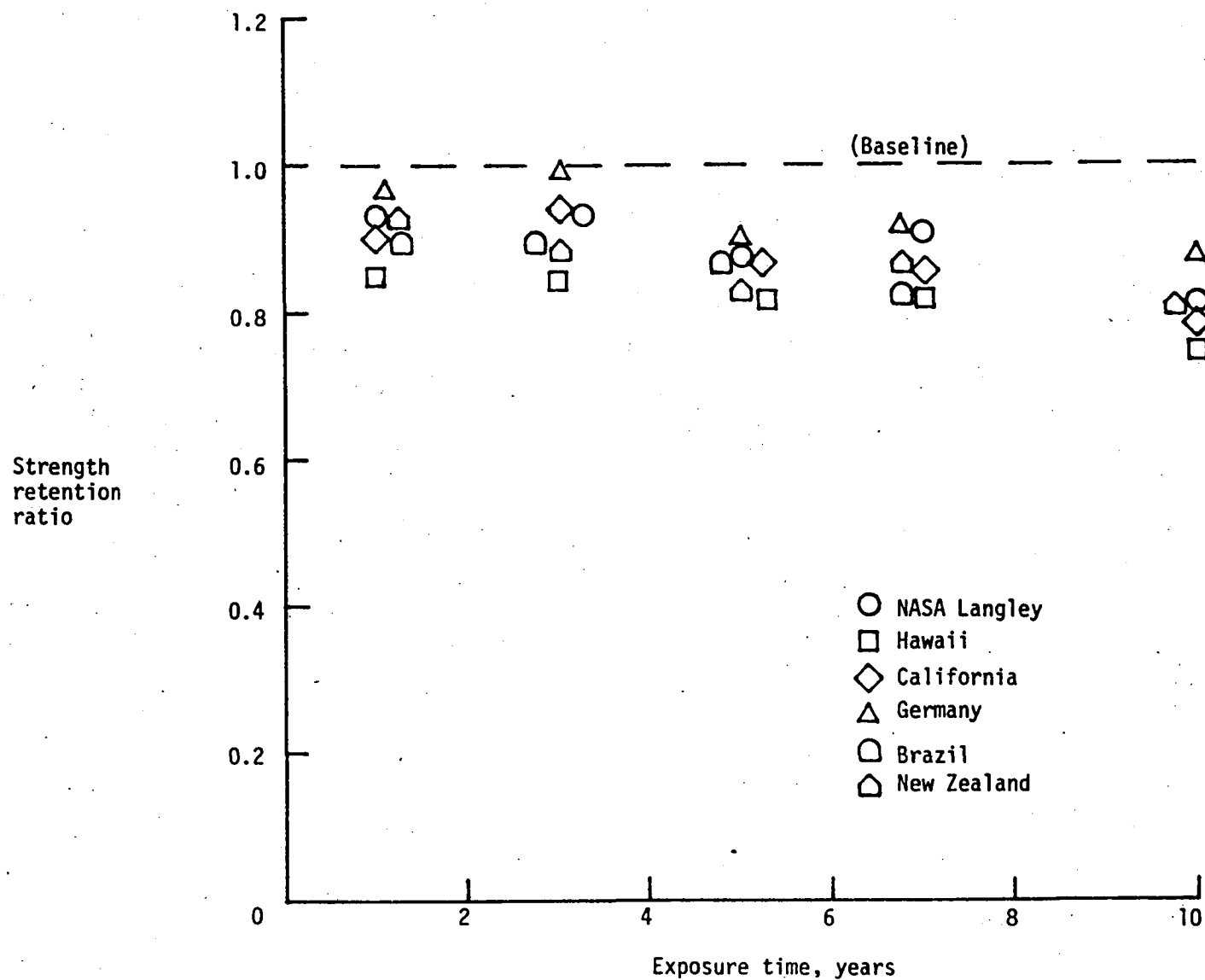


Figure 4. RT Flexure Strength Retention of Kevlar/F-155 After Outdoor Ground-Based Exposure.

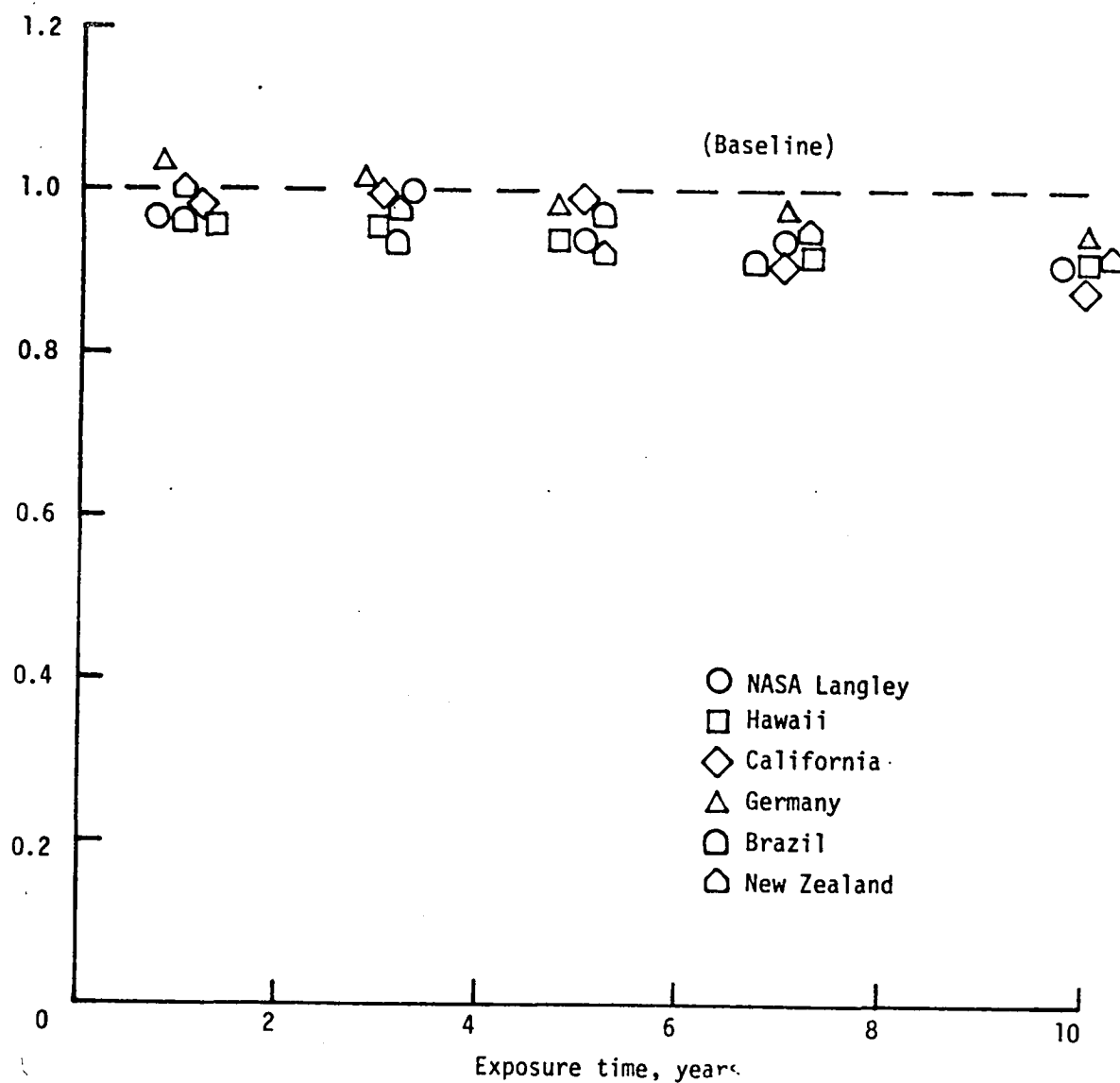


Figure 5. RT Flexure Strength Retention of Kevlar/F-161 After Outdoor Ground-Based Exposure.

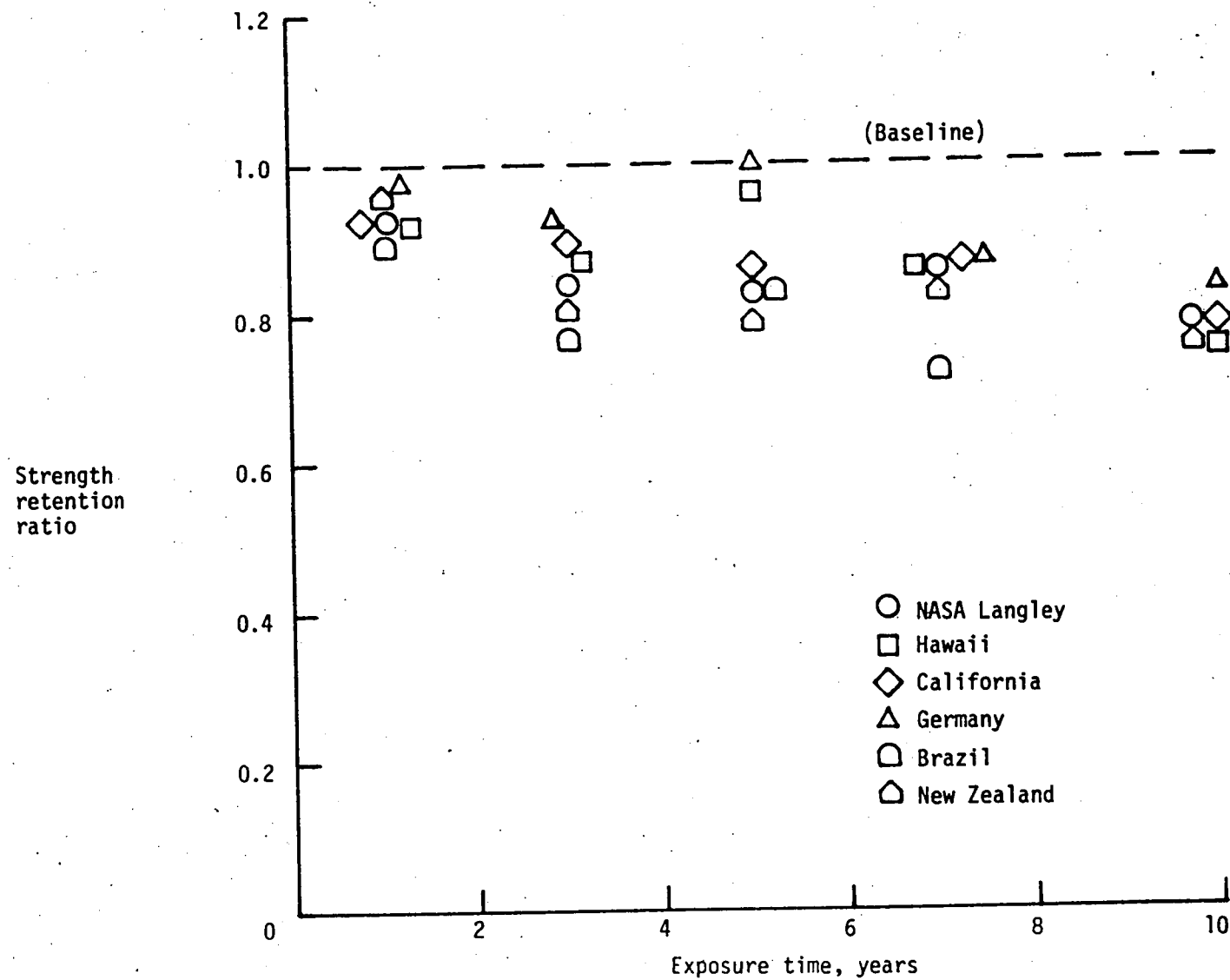


Figure 6. RT Short Beam Interlaminar Shear Strength Retention of Kevlar/F-155 After Outdoor Ground-Based Exposure.

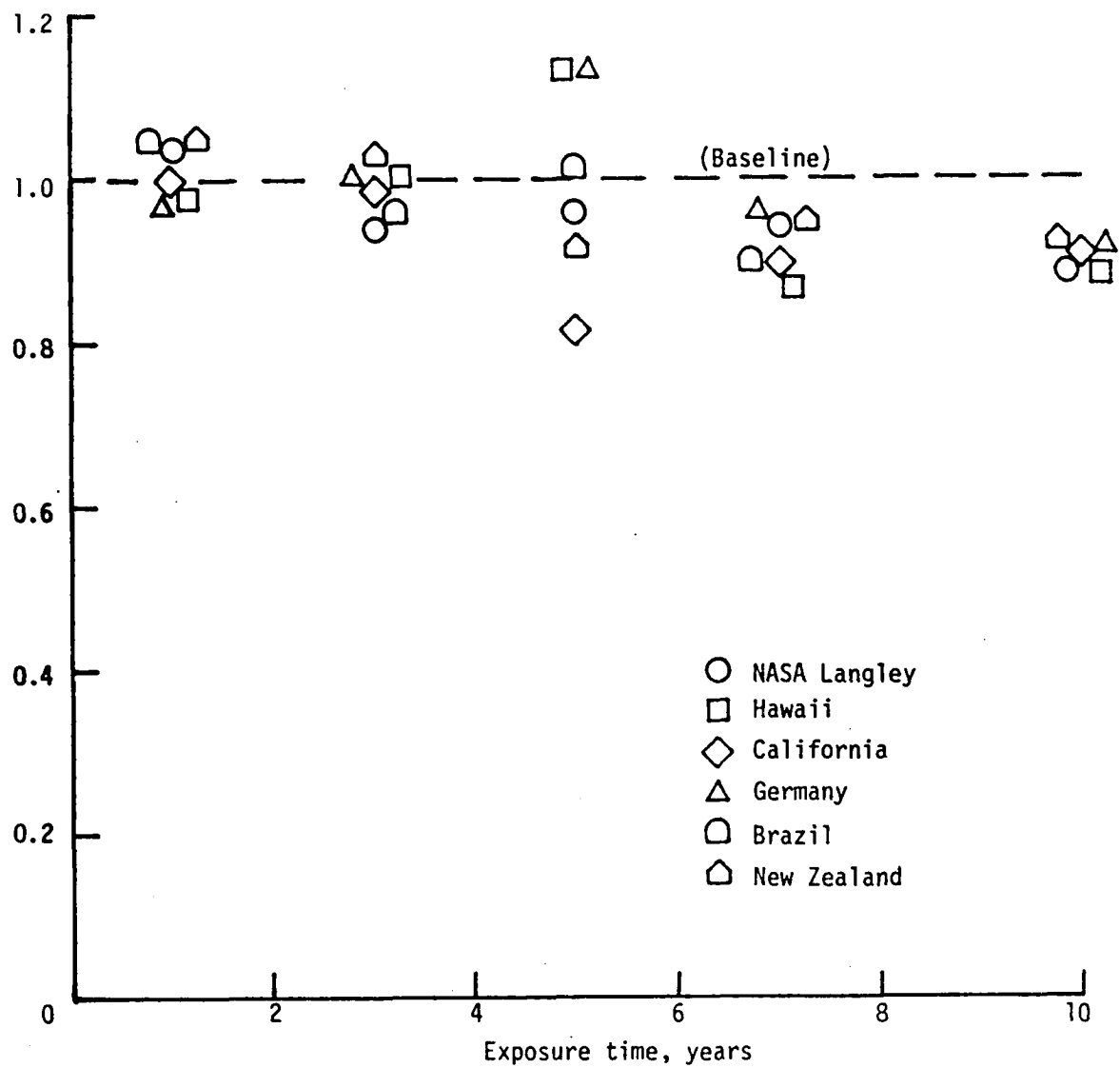


Figure 7. RT Short Beam Interlaminar Shear Strength Retention of Kevlar/F-161 After Outdoor Ground-Based Exposure.

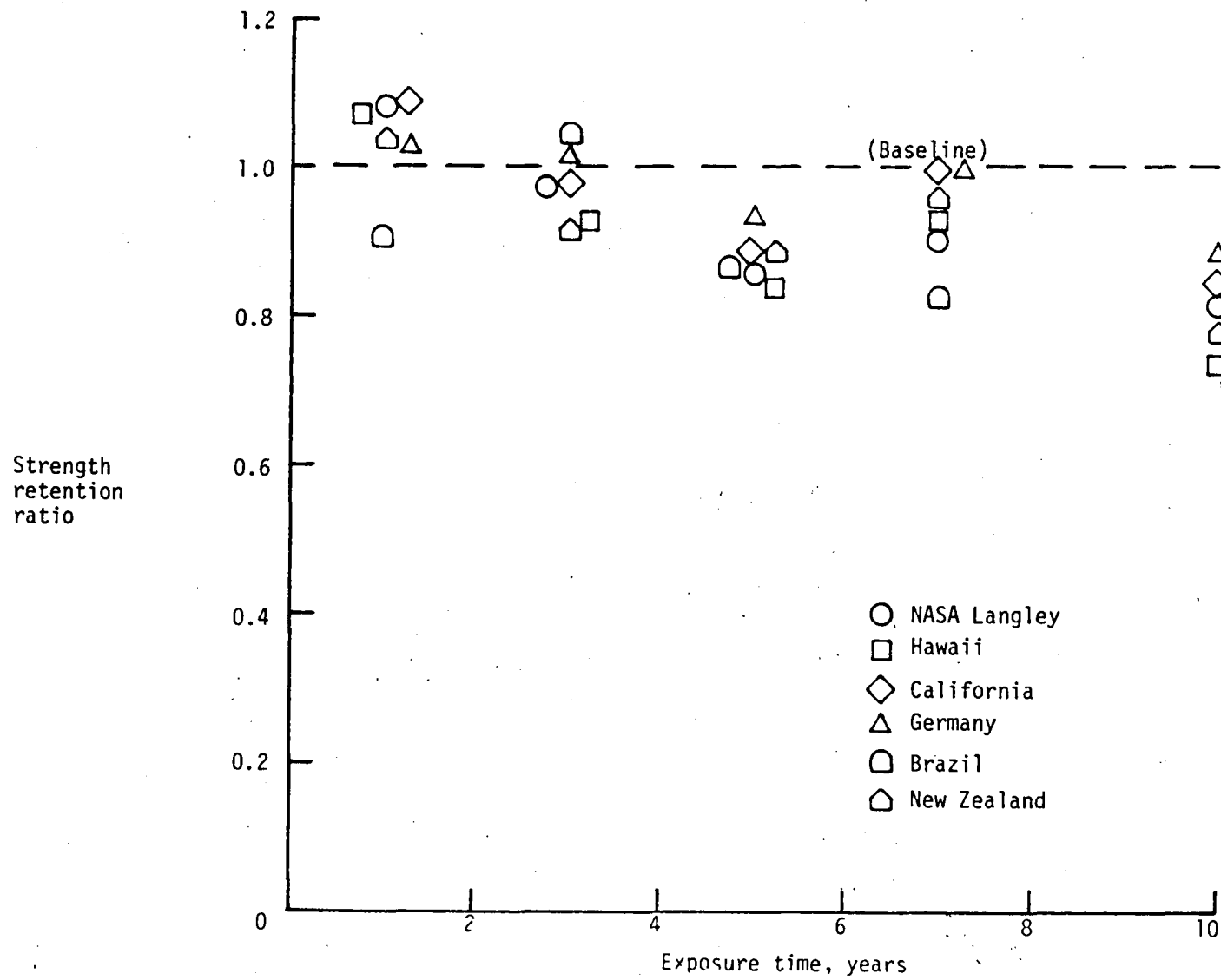


Figure 8. RT Compression Strength Retention of Kevlar/F-155 After Outdoor Ground-Based Exposure.

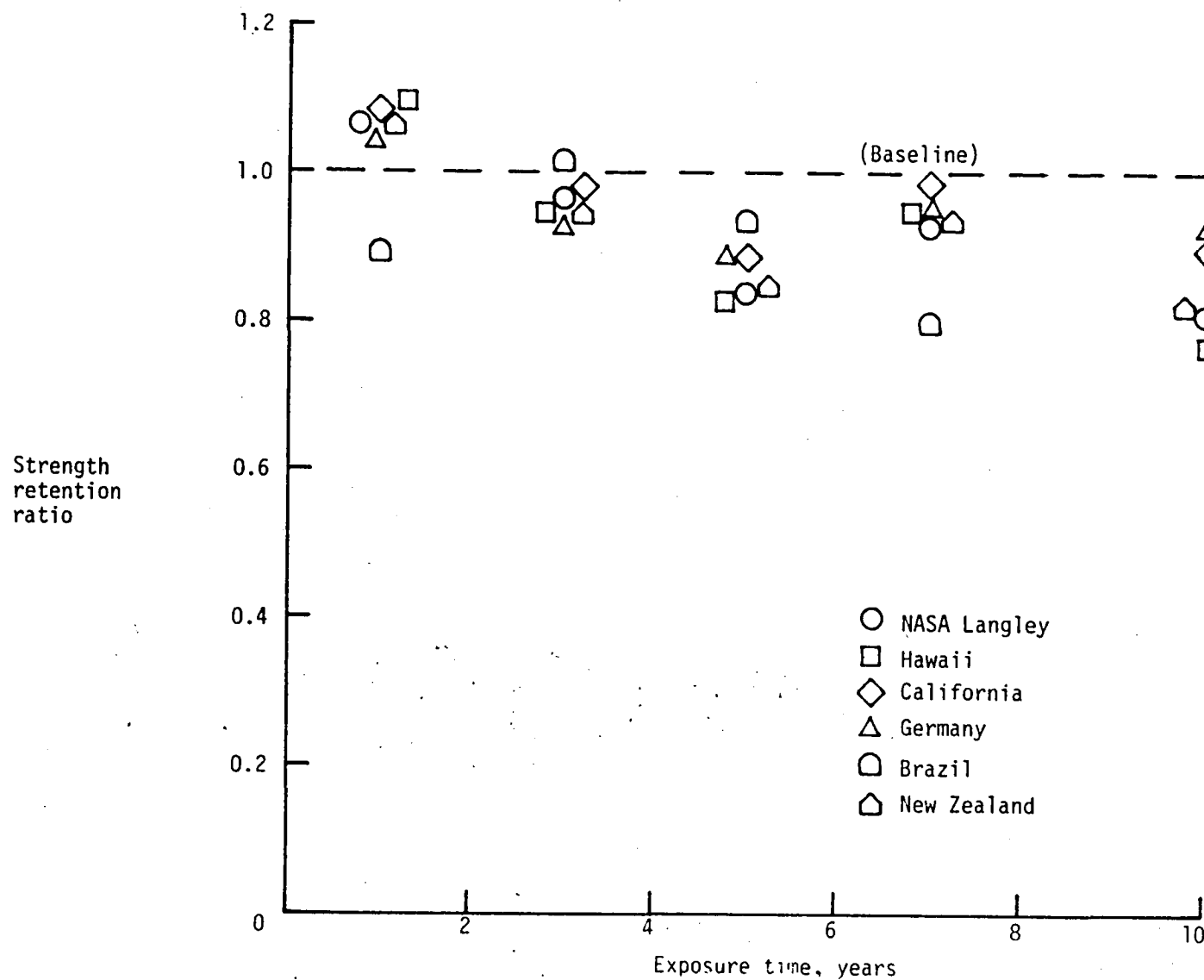


Figure 9. RT Compression Strength Retention of Kevlar/F-161 After Outdoor Ground-Based Exposure

The compression strength data also indicates significant scatter in strength during the ten year exposure period. Except for the Brazil exposure, an average strength increase of about seven percent is shown for all exposure locations after one year of exposure for the Kevlar/F-155 material (figure 8). These results may indicate that additional tests should have been conducted to establish a more representative baseline strength. An average strength reduction of 19 percent is shown after ten years of exposure. The specimens exposed to the Hawaii environment showed a 27 percent average strength reduction after ten years of exposure. A similar data trend is shown for the Kevlar/F-161 compression strength (figure 9). An average strength reduction of 16 percent is shown after ten years of exposure. The specimens exposed to the Hawaii environment showed a 23 percent average strength reduction after ten years of exposure.

Moisture absorption data have been obtained from flexure specimens at all six exposure sites during the ten year exposure period. Seven-year test results reported in reference 10 indicated a moisture saturation level slightly above two percent for both material systems. In general, the specimens exposed in Brazil absorbed the most moisture and the specimens exposed in California and Germany absorbed the least amount of moisture. The ten-year exposure specimens are currently being dried to determine moisture absorption.

SUMMARY OF RESULTS AND CONCLUSIONS

The Kevlar-49 fairing panels continue to perform satisfactorily and are free of major damage or defects after 10 years of service and a total of 79,568 flight hours on the three aircraft.

The following types of minor damage have been noted: cracks resulting from impact observed principally on the wing-body fairings; small disbond areas also noted primarily on the wing-body fairings; and fraying and elongation of fastener holes. The cracks are primarily the result of ground handling damage while the disbonds may be the result of impact, heat or manufacturing defects. The fastener hole fraying appears to be primarily the result of the

initial drilling and installation procedures, aggravated in a few instances by in-service loads; while the elongation is probably related to nonuniform bearing loads caused by installation mismatches or excessive hole clearances.

The absence of crack growth, disbond growth or significantly increased hole elongation, and the random limited occurrence of hole elongation indicates that Kevlar-49 is resistant to damage propagation under the relatively light loading conditions typical of fairings. The fastener hole fuzzing and frayed appearance is the only damage condition observed on the Kevlar-49 parts which is not also typical of similar fiberglass parts. The fuzzing has not increased in severity with increasing service life, and does not have any apparent effect on part performance.

The Kevlar-49 parts have been free of any defects which can be attributed to moisture or other environmental factors, and there has been no clear evidence of interply delaminations (as opposed to disbonds). These findings indicate that two properties of Kevlar-49 which were of initial concern - the poor resin-fiber interface bond and the moisture pickup of the Kevlar-49 fibers - have not seriously affected part performance.

The repairs which have been performed on these parts are typical cosmetic repairs, such as resin filling of surface cracks and applications of tape over damage areas. This type of repair is typically performed on fiberglass secondary structures, and these observations indicate that Kevlar-49 parts can be repaired in the same manner as fiberglass parts.

The ground-based environmental exposure tests performed by NASA Langley indicates that moisture absorption is stabilizing slightly above 2 percent. Ultraviolet exposure effects during the 10-year exposure period result in a net weight loss for the unpainted specimens tested in this program. However, painted aircraft structural components should not experience similar weight loss. Average strength reductions of about 20 percent were shown for the Kevlar/F-155 material after 10 years of exposures. Average strength reductions for the Kevlar/F-161 material after 10 years of exposure were about 10-15 percent.

In summary, Kevlar-49/epoxy provides service life and structural performance for lightly loaded secondary structures equivalent to that of fiberglass/epoxy over an extended flight-service period.

APPENDIX A

DETAIL OBSERVATIONS OF KEVLAR-49 FAIRING PANELS - EASTERN SHIP N313EA (SERIAL 1020)

JULY 1983

Two of the remaining four fairings were removed for inspection: the left-hand wing-body fairing and aft engine fairing panels. The right-hand wing-body fairing and aft engine fairing were inspected on the aircraft. The two underwing fillet panels were misplaced after their removal from the original aircraft in 1979.

LEFT-HAND WING-BODY FAIRING

1. A deep gouge and associated crack 2.5 cm (1 in.) in length in the upper forward area of the exterior surface was first observed in 1978. A repair consisting of a thixotropic resin filler forming a triangular patch approximately 12.9 cm² (2 in.²) in area was observed in 1979. In the following two years, the patch remained unchanged except for an overcoat of paint. This year a crescent shaped delamination 1.3 cm (1/2 in. radius) was observed adjacent to the filled area.
2. A speed tape patch first observed in 1975 on the exterior surface had been removed since the 1979 inspection, and presumably the damage had been filled with resin. This was detectable as a slightly depressed line, 6.3 cm (2-1/2 in.) long with delaminated or disbanded areas at each end, one 0.8 cm (5/16 in.) diameter and the other 0.5 cm (3/16 in.) diameter, which had the appearance of filled holes (figure A-1). This was essentially unchanged since the 1982 inspection. A second depressed line noted in 1982 was undetectable after repainting.
3. Two new disbond areas were observed on the exterior surface as follows:
 - An area 1.9 by 1.0 cm (3/4 by 3/8 in.) in the upper aft area
 - An area 0.8 by 0.6 cm (5/16 by 1/4 in.) in the upper forward area.
4. An area of exposed Kevlar was observed in the lower aft area, about 0.8 by 0.6 cm (5/16 by 1/4 in.). This area would have only slight exposure to ultraviolet, however.

5. A delaminated or disbonded area on the inner surface in the upper forward area has been observed since 1975 at which time it was a 1.3 cm (1/2 in.) diameter area with a delaminated strip 15.2 by 1.3 cm (6 by 1/2 in.) extending from it. This area has been noted to increase slightly at subsequent inspections, and it was measured this time at 28.5 cm (11-1/4 in.) in length with a width varying from 3.8 cm (1-1/2 in.) to 1.3 cm (1/2 in.).
6. A second delaminated or disbonded area was also observed on the upper forward area of the inner surface, 3.2 by 3.5 cm (1-1/4 by 1-3/8 in.) in area. This had not increased in size since the 1981 inspection.
7. Most of the fastener holes were observed to have at least a slight degree of fraying. Several holes were noticeably more frayed (figure A-2) than the others, including two holes in the forward edge and eight holes on the lower edge. These fasteners holes had been redrilled upon reinstallation of these fairings in 1979, and several of these holes had a more pronounced fuzziness and frayed appearance than any holes previously observed in this program.
8. Most of the holes showed some degree of elongation. Out of approximately 50 holes on this part, 8 holes were elongated to 0.55 cm (7/32 in.) from the original 0.5 cm (3/16 in.) dimension; 23 holes were elongated to 0.6 cm (1/4 in.); 4 holes were elongated to 0.7 cm (9/32 in.); and 2 holes were elongated to 0.8 cm (5/16 in.). The elongated areas tended to be areas without the frayed condition, and in most cases it could be seen that the elongation was occurring in the filler. The filler is a chopped glass fiber filled epoxy resin used to fill the original fastener holes.

LEFT-HAND AFT ENGINE FAIRING

1. No damage or defects were noted on either surface. A small depression on the exterior surface noted in the 1982 inspection was not detectable after repainting.
2. Despite the repainting, some areas of paint loss due to Skydrol were observed. These were primarily in the aft area of the part.
3. Most of the fastener holes in this part were redrilled through the Kevlar-49 and were fully offset from the filled area (figure A-3). These holes were all extremely frayed (figure A-4), and the fuzziness and frayed condition was noticeably worse than the holes previously observed on this program. Elongation was noted in about 12 holes (out of a total of approximately 110 holes), and this elongation occurred mainly in areas where the hole was redrilled through a portion of the filled original hole. The elongations ranged from 0.55 cm (7/32 in.) to 0.7 cm (9/32 in.) compared to the original 0.5 cm (3/16 in.) diameter. The degree of fraying had not increased since the redrilled holes were first observed in the 1981 inspection.

4. All fasteners on the lower edge had reduced edge distances in some cases as low as 0.4 cm (5/32 in.).

RIGHT-HAND WING-BODY FAIRING

1. Several exterior surface cracks observed in previous inspections had not propagated or increased in size since the 1982 inspection:
 - A 1.3 cm (1/2 in.) crack in the forward edge between the fifth and sixth holes from the top first observed in 1976.
 - A 0.3 cm (1/8 in.) ding in the lower center area first observed in 1976.
 - A 0.3 cm (1/8 in.) crack in the aft center area first observed in 1975.
 - A 0.6 cm (1/4 in.) crack in the center area first observed in 1976 and observed as a depressed area in 1982 after repainting.
 - A 0.8 cm (5/16 in.) crack in the upper forward area first observed in 1977.
2. A delaminated or disbonded area in the lower forward area of the exterior surface had increased in size from 1.4 by 0.8 cm (9/16 by 5/16 in.) in 1982 to 3.8 by 2.5 cm (1-1/2 by 1 in.) in 1983. Slight growth was also observed in a smaller delamination in the lower forward area; from 1.6 by 0.95 cm (5/8 by 3/8 in.) in 1982 to 1.9 cm (3/4 in.) diameter.
3. A slight depression in the upper aft area of the exterior surface was essentially unchanged since 1982 at a size of 0.9 by 0.3 cm (3/8 by 1/8 in.).

RIGHT-HAND AFT ENGINE FAIRING

1. There was no visible damage or paint loss on the exterior surface.

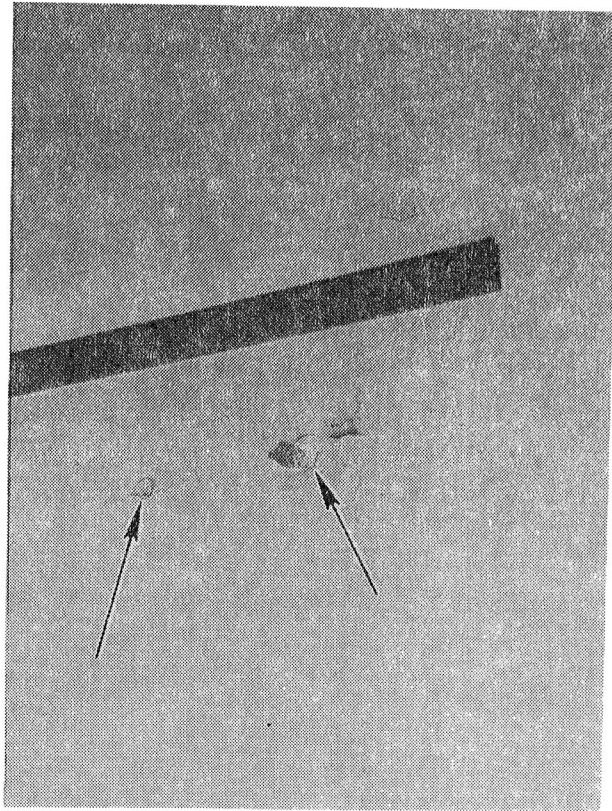


Figure A-1. - Eastern left-hand wing-body fairing - delamination areas connected by depression line.

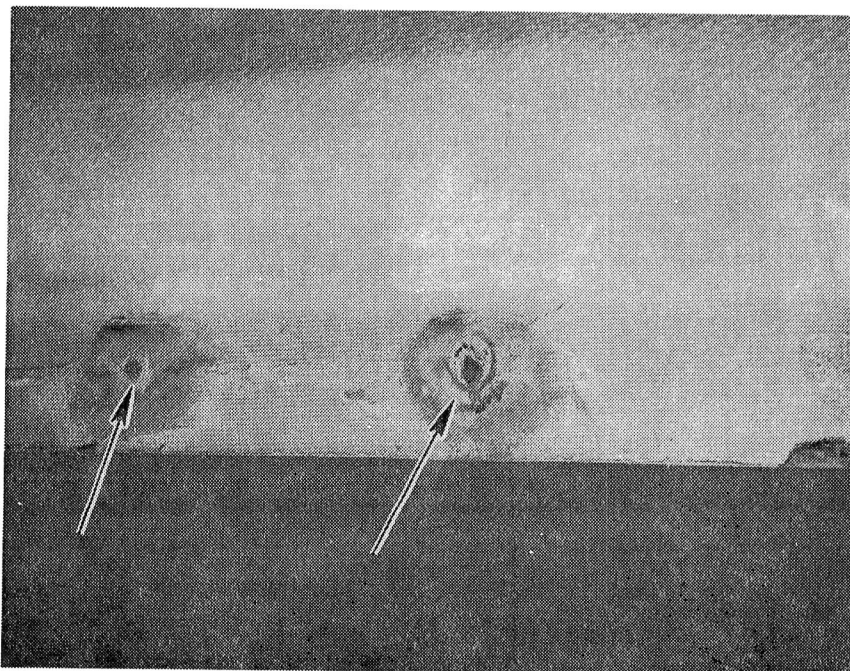


Figure A-2. - Eastern left-hand wing-body fairing - badly frayed holes.

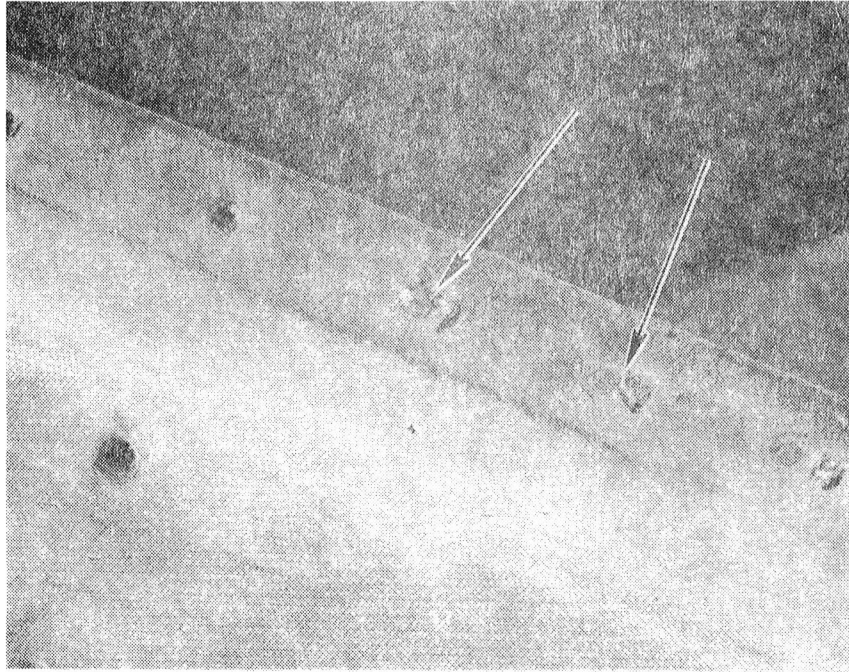


Figure A-3. - Eastern left-hand aft engine fairing - redrilled fastener holes partially and fully offset from filled holes.

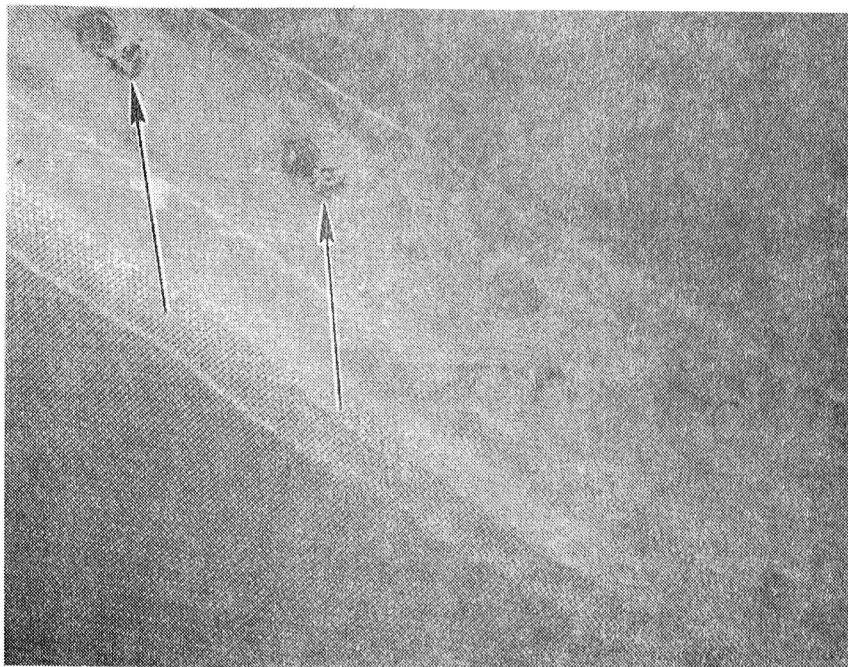


Figure A-4. - Eastern left-hand aft engine fairing showing extreme frayed condition of redrilled holes.

APPENDIX B

DETAIL OBSERVATIONS OF KEVLAR-49 FAIRING PANELS - TWA SHIP N31030 (SERIAL 1111)

OCTOBER 1983

Three of the six fairings were removed for inspection: the left-hand wing-body fairing and the right-hand underwing fillet and aft engine fairing panels. The other panels were inspected in place on the aircraft. Mass determinations were made on the right-hand fillet panel.

LEFT-HAND WING-BODY FAIRING

1. A tape patch repair of a deep gouge, first observed in 1980, on the exterior surface was still in place with no changes in appearance since the previous inspection (figure B-1). There was some paint loss near the patch, but no delamination or evidence of damage growth.
2. Another repair, on the exterior surface was first observed in 1980, and consisted of a 0.3 cm (1/8 in.) crack filled with resin. The repair was unchanged in appearance with no crack propagation.
3. An area of extensive paint loss along the forward edge was still present indicating probable Skydrol exposure (figure B-2). This area had not increased significantly since it was first noted in the 1982 inspection. Flame spray was intact in this area preventing any exposure of the Kevlar to ultraviolet.
4. A crack 1.3 cm (1/2 in.) in total length was noted in the upper aft area of the inner skin (figure B-3). The crack completely penetrated the skin, and had associated delamination extending 0.3 cm (1/8 in.) on both sides of the crack. This damage had not been observed previously.
5. Another new damage area on the inner skin was a 0.5 cm (3/16 inch) diameter delamination or disbond in the lower aft area.
6. Slight fraying was observed on most fastener holes, but in general this part has less fraying than the other wing-body fairing panels (figure B-4). Several holes were elongated to a measurable extent: four holes to 0.55 cm (7/32 in.) from the original 0.5 cm (3/16 in.) dimension, four holes to 0.6 cm (1/4 in.), and one hole to 0.7 cm (9/32 in.). These holes tended to be more frayed than the others. This was a slight increase in elongation since the 1981 inspection.

RIGHT-HAND UNDERWING FILLET

1. The panel mass was 671.8g (1.481 lb). Previous mass determinations were 670.4g in the 1982 inspection, 671.0g in the 1981 inspection, 664.0g in 1980, 664.6g in 1979, and 663.75g in 1978. The changes in mass are due to paint loss and repainting.
2. No surface damage or defects were observed. Paint was chipped in the lower aft area exposing the Kevlar surface. This is an area not subject to ultraviolet exposure.
3. All of the fastener holes were at least slightly frayed, and eight of the twenty holes were badly frayed (figure B-5). Six holes were observed to have measurable elongation: five holes to 0.55 cm (7/32 in.) from the original 0.5 cm (3/16 in.), and one hole elongated to 0.7 cm (9/32 in.). Some of the elongated holes were among the badly frayed holes, but the two conditions did not correlate exactly.

RIGHT-HAND AFT ENGINE FAIRING

1. There was no damage to either surface. Loss of paint and flame spray had left some exposed Kevlar-49 surface. The vapor barrier coating, which had been applied to the inner surface during reinstallation to replace the Tedlar film, had been chemically attacked in several areas, probably by Skydrol. One area of the vapor barrier coating near the upper aft corner had become blackened and Flaky (figure B-6). These conditions had not changed significantly since the previous inspections of this part in 1979 and 1981.
2. The frayed condition noted on other panels was almost completely absent from this part with only one noticeably frayed hole. All holes on this part had been relocated at the time of reinstallation, and a surface layer of resin impregnated 120 fiberglass fabric had been bonded to both surfaces prior to drilling the relocated holes. This effectively eliminated the fuzziness or frayed condition noted on the other parts. (figure B-7).
3. There were a significant number of elongated holes (figure B-7). Twenty-two holes were measured at 0.55 cm (7/32 in.) from the original 0.5 cm (3/16 in.) diameter; 12 holes were measured at 0.6 cm (1/4 in.); and two holes were measured at 0.7 cm (9/32 in.). The above included three holes in the intercostals which were drilled through the honeycomb. These elongated holes constituted about 30 percent of the total. Since all holes were relocated, it appears probable that the filled hole areas accounted for the high incidence of elongation.

RIGHT-HAND WING-BODY FAIRING

1. Only one clearly defined damage area was observed on the exterior surface. This was a deep gouge in the upper aft area first noted in 1981. This was measured at 0.6 cm (1/4 in.) length with a delamination or disbond area about 1 cm (3/8 inch) in diameter. Several small cracks observed in previous inspections were not detected, indicating they had been only in the paint.
2. A large teardrop shaped disbonded and crushed area, 11.4 by 2.5 cm (4-1/2 by 1 in.) had not changed in size or appearance since the previous inspection (figure B-8). This was first observed in 1977, and is in the lower forward area of the exterior surface at the possible location of a repair. A small depressed area in the lower forward area of the exterior surface, first observed in 1978, had not changed since the previous inspection. These may represent areas where some force has caused core crushing without skin penetration, and in the smaller area without a skin-core disbond.
3. A rectangular patch overlay 10 by 20 cm (4 by 8 in.) on the lower forward edge of the exterior surface was unchanged in appearance since the previous inspection. This was first observed in 1978, but no damage had been previously observed in that area.

LEFT-HAND UNDERWING FILLET

1. Only the lower section of this part was visible. There were no surface defects, damage areas, or paint loss. The lower aft edge was bulged in appearance indicating a possible slight mismatch of fastener holes. A missing fastener was again noted in the lower section.

LEFT-HAND AFT ENGINE FAIRING

1. There was no visible damage to the exterior surface. Paint loss areas observed in previous inspections had been touched up, but in a few small areas the flame spray was still missing, exposing the Kevlar-49 surface to ultraviolet.

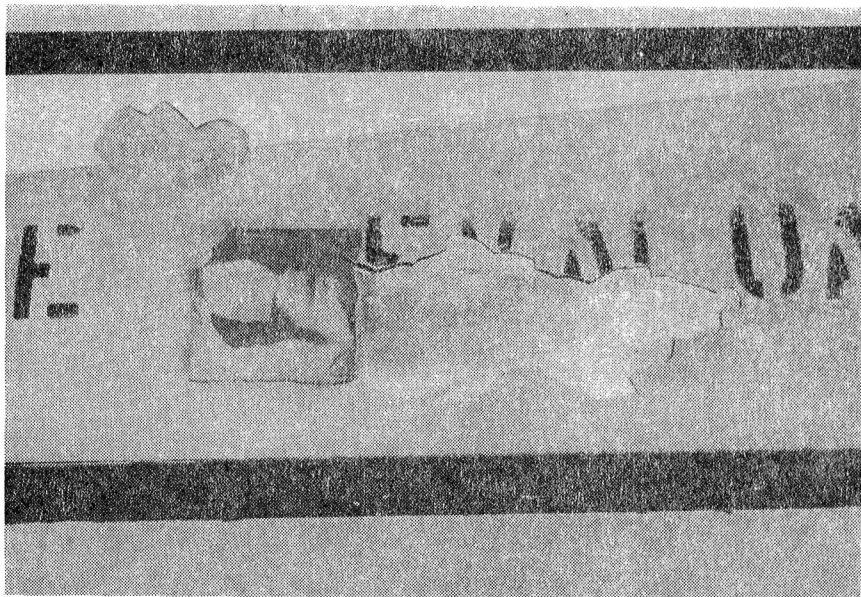


Figure B-1. - TWA left-hand wing-body fairing - tape patch repair of deep gouge.

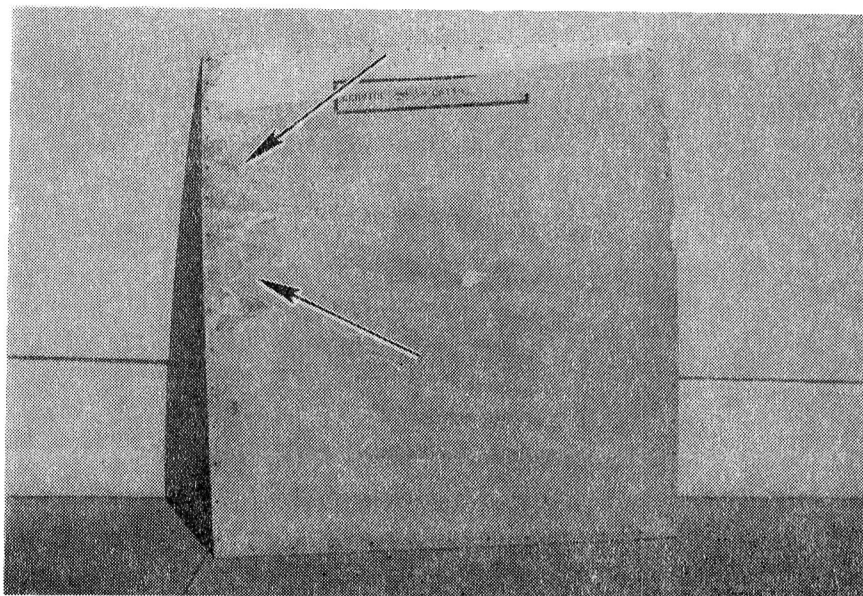


Figure B-2. - TWA left-hand wing-body fairing - exterior surface showing paint loss area.

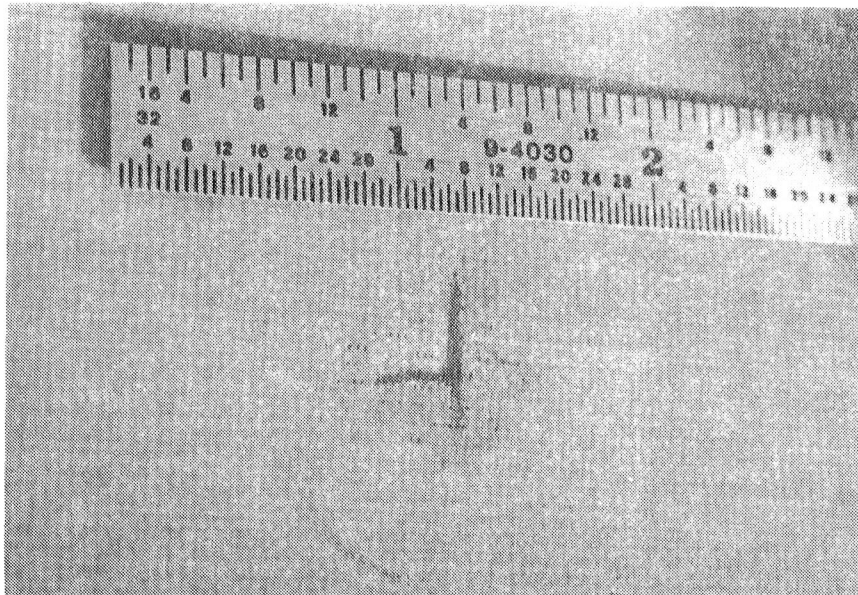


Figure B-3. - TWA left-hand wing-body fairing - crack and skin penetration on inner surface.

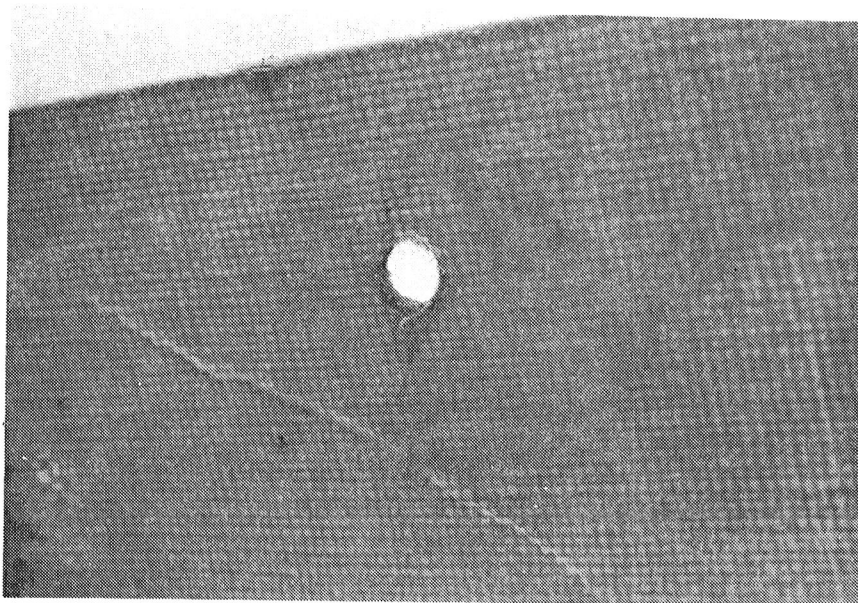


Figure B-4. - TWA left-hand wing-body fairing - typical fastener hole with slight fraying.

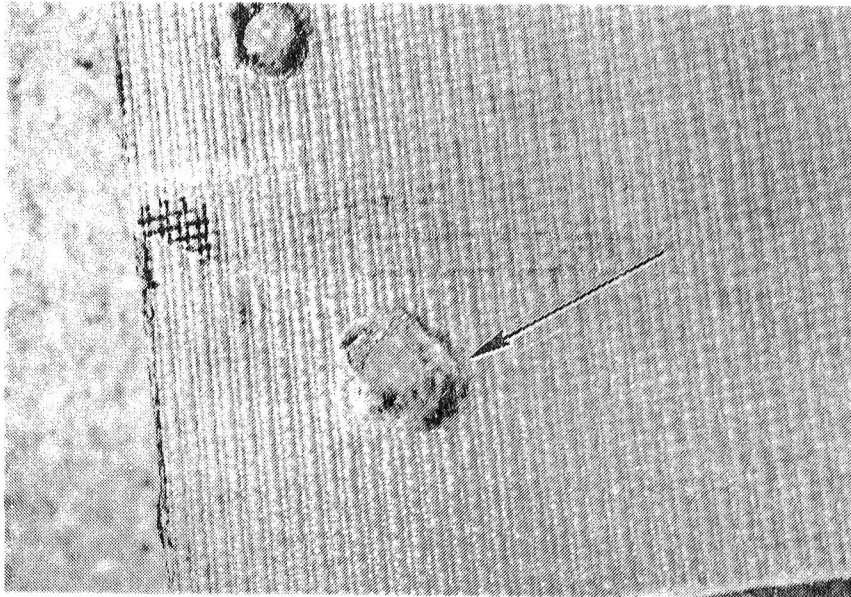


Figure B-5. - TWA right-hand underwing fillet - badly frayed holes.

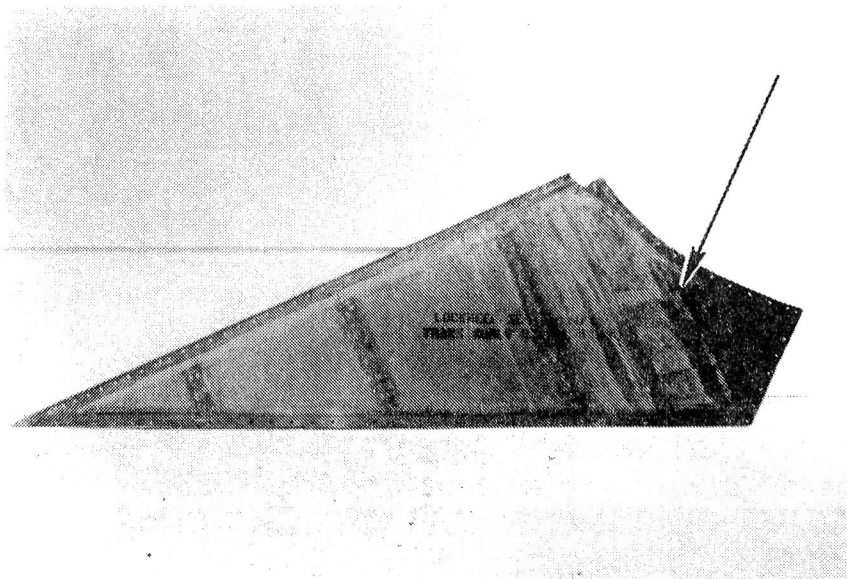


Figure B-6. - TWA right-hand aft engine fairing - inner surface showing Skydrol attack on coating.

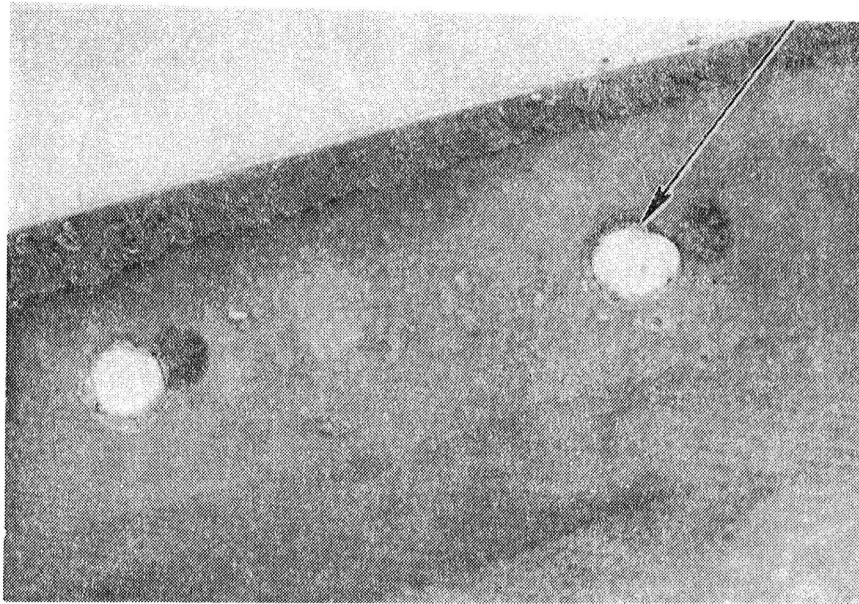


Figure B-7. - TWA right-hand aft engine fairing - fastener holes showing elongation and absence of fraying.

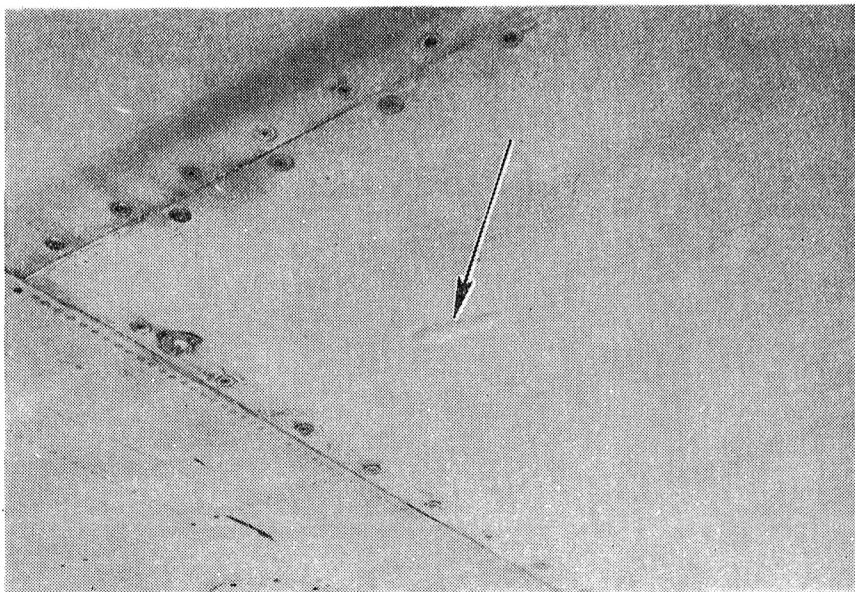


Figure B-8. - TWA right-hand wing-body fairing on the aircraft showing large disbond area.

APPENDIX C

DETAIL OBSERVATIONS OF KEVLAR-49 FAIRING PANELS - AIR CANADA SHIP CF-TNB-502 (SERIAL 1021)

FEBRUARY 1984

Three of the six fairings were removed for inspection: the left-hand wing-body fairing and underwing fillet panels, and the right-hand aft engine fairing. The other panels were inspected in place on the aircraft.

LEFT-HAND WING-BODY FAIRING

1. A deep gouge in the upper aft area of the exterior surface had grown slightly in area from 0.4 by 0.6 cm (5/32 by 1/4 inch) to 0.95 by 0.6 cm (3/8 by 3/4 inch) (figure C-1). There was still a delaminated area, 0.3 by 0.6 cm (1/8 by 1/4 inch) in area adjacent to the gouge.
2. Several small gouges on the lower forward edge observed in previous inspections, were not detectable after a repainting and filling operation.
3. A repair of a 3.2 cm (1-1/4 inch) long crack in the upper aft area of the exterior surface, made after the 1977 inspection, had not changed in appearance since that time, and there was no associated delamination. The area painted over was approximately 6.4 by 2.5 cm (2-1/2 by 1 inch).
4. Three new delaminations or disbonds were noted on the exterior surface: a 3.5 by 1.6 cm (1 3/8 by 5/8 inch) delamination in the upper aft area; a 1.6 by 1.3 cm (5/8 by 1/2 inch) delamination in the lower forward area; and a 1/3 by 2.2 cm (1/2 by 7/8 inch) delamination also in the lower forward area.
5. Three shallow pits encompassing an area 1.9 cm (3/4 inch) in area was observed in the lower forward area of the exterior surface. These may be only in the paint, as no associated delamination or disbond was observed.
6. A deep crack in the upper forward area of the inner surface, 1.3 cm (1/2 inch) in length, had not increased in size since the previous inspection (figure C-2).
7. Two delaminated areas on the inner surface, observed in previous inspections, had increased slightly in area since the previous inspection. These were a 1.3 by 0.6 cm (1/2 by 1/4 inch) delamination in the upper forward area, and a 1.3 by 0.6 cm (1/2 by 1/4 inch) delamination in the lower aft area.

8. A crack 1.5 cm (9/16 inch) in length was observed in the upper forward area of the inner surface with an associated delamination 0.3 cm (1/8 inch) wide. This had grown from 0.8 cm (5/16 inch) length observed in the 1982 inspection.
9. The fastener holes on the top and forward edges showed slight fraying; the holes on the aft edge and particular on the lower edge showed a greater degree of fraying. This condition has not changed significantly over the last few years of observation.
10. Several holes were elongated including two holes on the top and forward edges, three holes in the aft edge, and one hole on the lower edge. The holes were all elongated to 0.55 cm (7/32 inch) from the original 0.5 cm (3/16 inch) diameter, except for one hole elongated to 0.6 cm (1/4 inch). The holes on the lower edge had mark-off from the nut plates on the inner surface (figure C-3). A typical hole showing no elongation and very slight fraying is shown in figure C-4. The conditions of the fastener holes had not changed significantly since the previous inspection.

LEFT-HAND UNDERWING FILLET

1. There was no visible damage or delaminated areas. The upper portion which is shielded from ultraviolet exposure had 95 percent paint loss with exposed Kevlar.
2. All of the fasteners showed some degree of fraying, with 8 holes out of 20 showing a severe degree of fraying.
3. Nine holes were elongated; seven holes to 0.55 cm (7/32 inch) diameter and two holes to 0.6 cm (1/4 inch) diameter.
4. The degree of fraying has not increased since the start of the fairing inspection. A slight and gradual increase has been noted in the degree of hole elongation. The two conditions are sometimes but not necessarily related. A frayed and elongated hole is shown in figure C-5, and a hole showing no elongation and slight fraying is shown in figure C-6.

RIGHT-HAND AFT ENGINE FAIRING

1. There was no visible damage or delaminated or disbanded areas. The part had been repainted since the previous inspection.
2. All the fastener holes showed a very slight degree of fraying (figure C-7). This part has a lesser degree of fraying than most of the other flight service fairings.

3. Only three holes, out of a total of 113 holes, were elongated: two holes along the intercostals (which are drilled through the core) were slightly elongated to 0.55 cm (7/32 inch), and one hole on the top edge was elongated to 0.7 cm (9/32 inch) (figure C-7).

RIGHT-HAND WING-BODY FAIRING

1. Two small cracks on the exterior surface had not changed since the previous inspection: a 0.6 cm (1/4 inch) crack in the upper forward area with an associated delaminated or disbonded area 0.95 cm (3/8 inch) wide; and a 0.3 cm (1/8 inch) crack in the upper aft area, also with a slight, 0.3 cm (1/8 inch) wide, delaminated area.
2. A delaminated and depressed area had significantly grown in area, from 4.1 by 1.2 cm (1 5/8 by 1/2 inch) in 1982 to 19.05 by 1.6 cm (7 1/2 by 5/8 inch) in area.

RIGHT-HAND UNDERWING FILLET

1. No visible damage or defects were noted on the exterior surface.

LEFT-HAND AFT ENGINE FAIRING

1. No visible damage or defects were noted on the exterior surface. The aft portion was accessible for coin tapping, and there were no disbond areas.

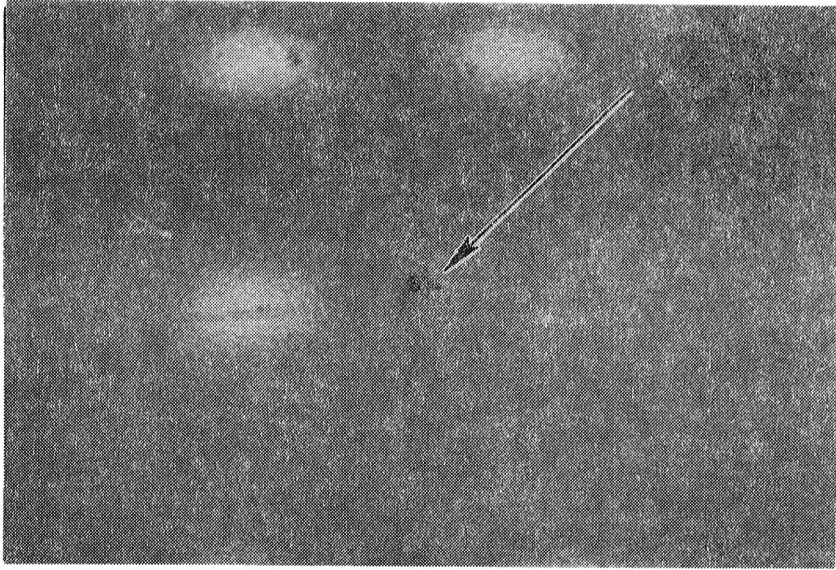


Figure C-1. - Air Canada left-hand wing-body fairing - deep gouge on exterior surface.

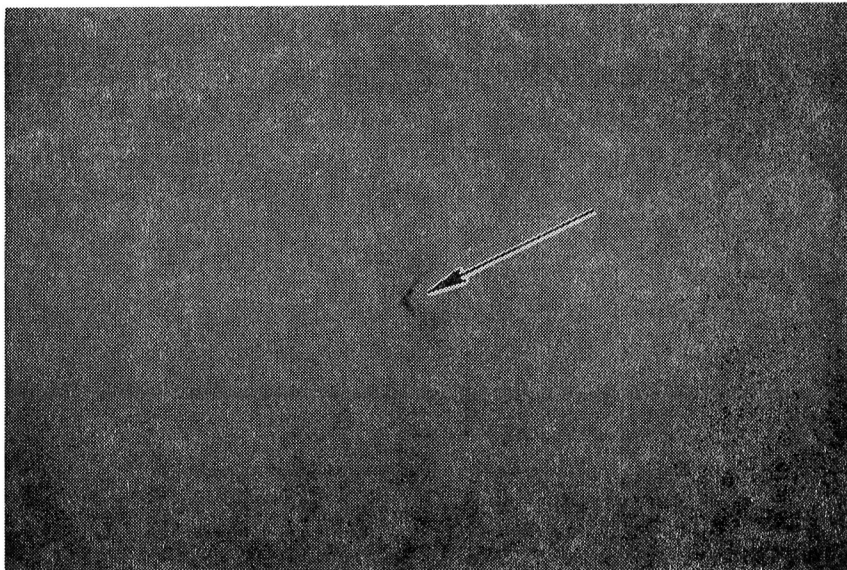


Figure C-2. - Air Canada left-hand wing-body fairing - crack on inner surface 1.3 cm (1/2 inch) length.

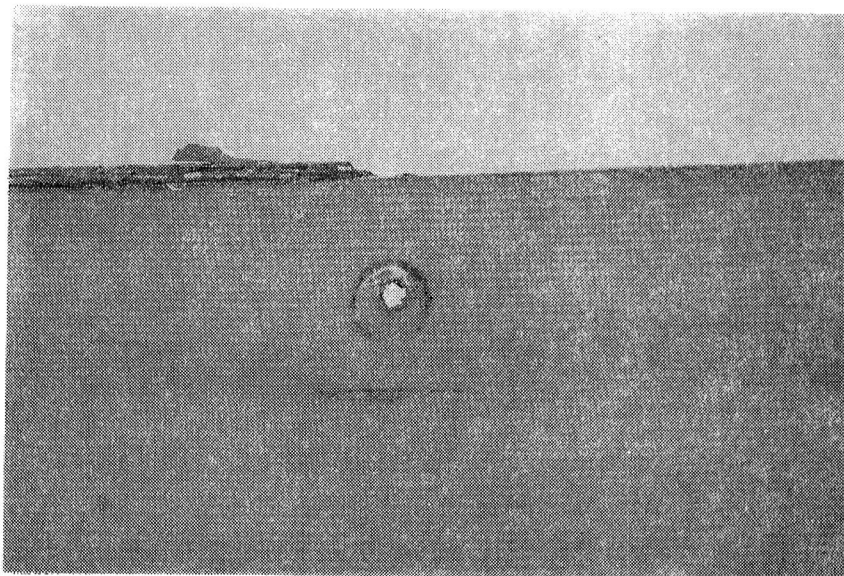


Figure C-3. - Air Canada left-hand wing-body fairing - fastener hole on lower edge with mark-off, slight fraying.

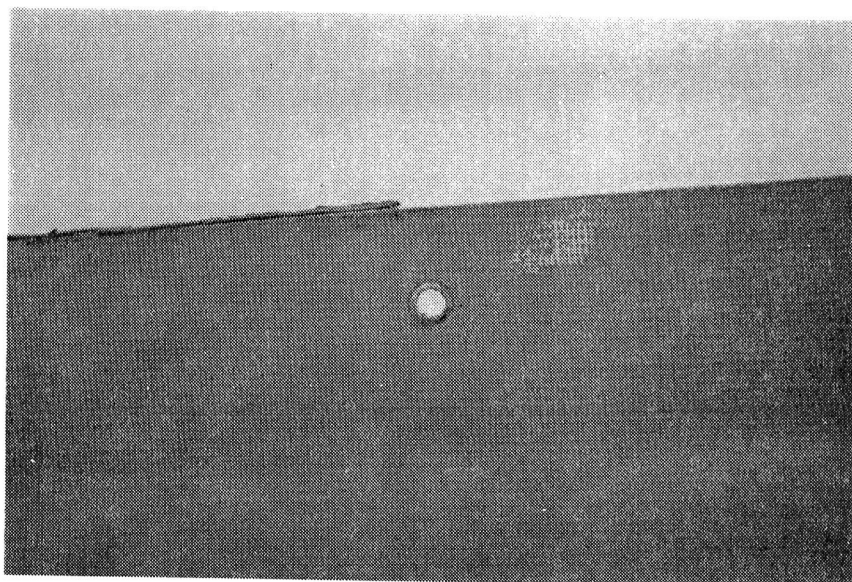


Figure C-4. - Air Canada left-hand wing-body fairing - typical hole with very slight fraying and no elongation.

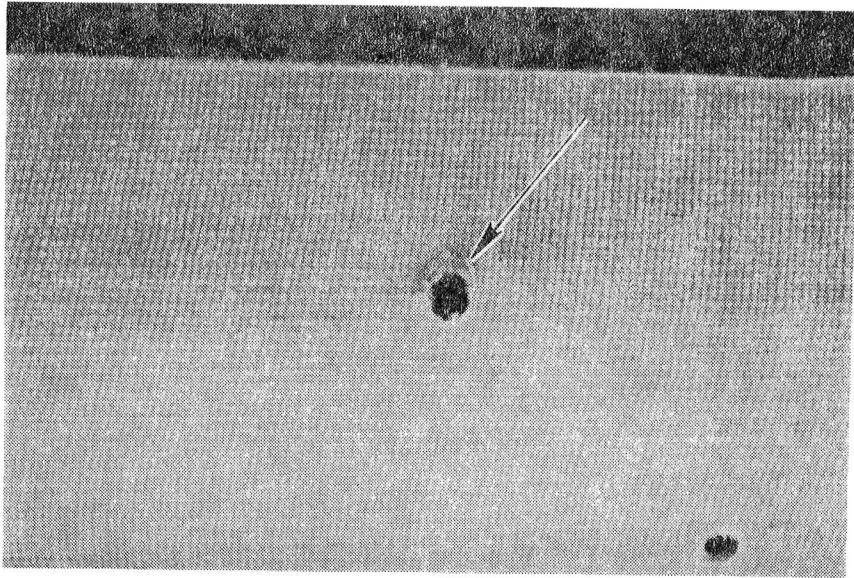


Figure C-5. - Air Canada left-hand underwing fillet - badly elongated and frayed hole.

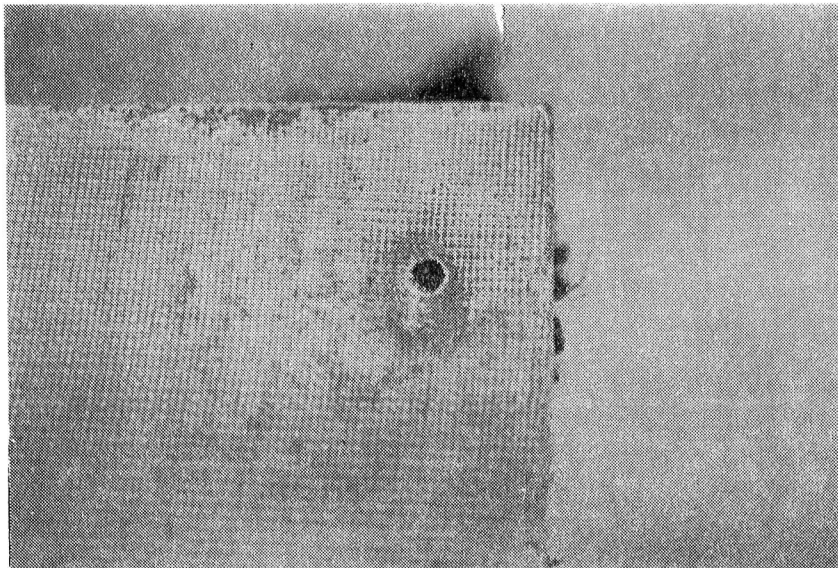


Figure C-6. - Air Canada left-hand underwing fillet - typical hole with very slight fraying, no elongation.

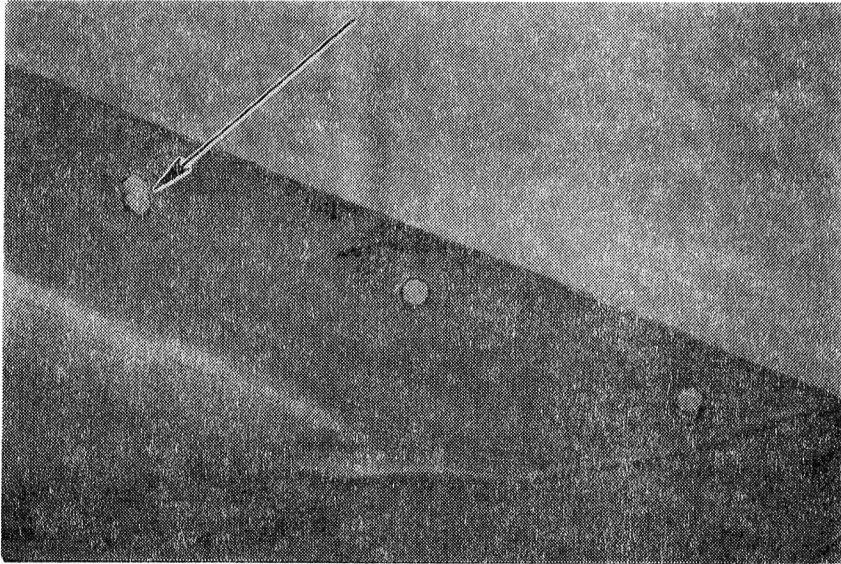


Figure C-7. - Air Canada right-hand aft engine fairing - typical holes with very slight fraying; badly elongated hole.

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16. Abstract <p>Kevlar-49 fairing panels, installed as flight service components on three L-1011s, were inspected after 10 years of service. There are six Kevlar-49 panels on each aircraft: a left-hand and right-hand set of a wing-body sandwich fairing; a solid laminate under-wing fillet panel; and a 422 K (300°F) service aft engine fairing. The three L-1011s include one each in service with Eastern, Air Canada, and TWA. The fairings have accumulated a total of 79,568 hours, with one ship set having nearly 28,000 hours service. The inspections were conducted at the airlines' major maintenance bases with the participation of Lockheed Engineering.</p> <p>The Kevlar-49 components were found to be performing satisfactorily in service with no major problems, or any condition requiring corrective action. The only defects noted were minor impact damage, a few minor disbonds and a minor degree of fastener hole fraying and elongation. These are for the most part comparable to damage noted on fiberglass fairings.</p> <p>The service history obtained in this program indicates that Kevlar-49 epoxy composite materials have satisfactory service characteristics for use in aircraft secondary structure.</p>					
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